

Fracture Driven Interactions: Frac Hit Risk Reduction, Casing Damage Potential, and Real Time Warning Signs

George E. King, P.E.

Viking Engineering

27 July 2019

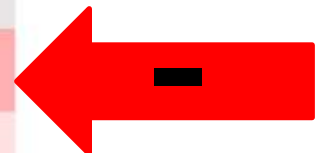
SPE Mid Continent Section, Tulsa OK



Shale Specific +/- Ranges (SPE 180200)

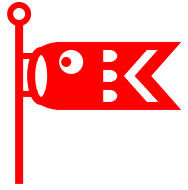
Table 1—Probability of effects from child wells fractured <2,000 ft and more than 18 months from parent well's date of first production.

SPE-180200-MS	Bakken	Eagle Ford	Haynesville	Woodford	Niobrara
<i>Positive Hit - Long Term</i>	17%	9%	20%	2%	0%
<i>Positive Hit - Short Term</i>	33%	14%	38%	2%	6%
Positive Hit Total	50%	24%	58%	4%	6%
No Change	35%	36%	24%	32%	38%
Negative Hit Total	15%	41%	19%	64%	56%
<i>Negative Hit - Short Term</i>	7%	13%	5%	20%	19%
<i>Negative Hit - Long Term</i>	6%	17%	5%	41%	31%
<i>Shut-in Post Offset Hit</i>	2%	10%	9%	3%	6%
Instances Included	649	1,210	366	259	32
<i>Original No. of Instances</i>	827	1,561	449	283	49
<i>Instances with Invalid Data</i>	178	351	83	24	17



My Observation: Refracs more successful in areas where positive impacts from frac intersections are common. ?

Foreseeable & Controllable factors that enable FDI's or level of damage



Design Factors

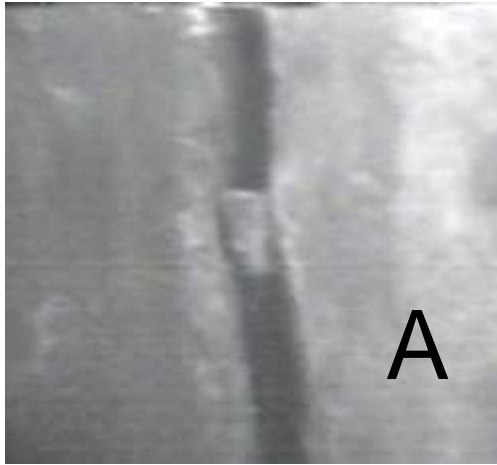
1. Well-to-well alignment
2. Well-to-well spacing
3. Frac-to-frac spacing
4. Well-to-frac plane alignment
5. Perf-cluster –to – offset perf cluster alignment along frac plane
6. Frac type (fluid, rate, prop loading)
7. Speed of rate (& pressure) application during ramp-up
8. Volume of the frac entering a single perf cluster.
9. **Fracturing in or near pressure depleted areas of offset wells.**
10. **Offset wells crossing the same fault plane**
11. **Poor cement quality in the lateral**

Less Controllable: geology, fabric, Insitu stresses, changing stresses, barriers, etc.

Damage may be Physical, Mechanical or Chemical

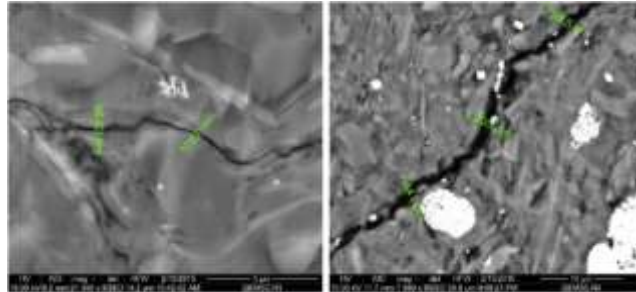
Difference in Hydraulic Fracs and Natural Fractures.

Bridging starts with particles
 $1/3^{\text{rd}}$ to $1/7^{\text{th}}$ the width of the frac.



A

Open planar frac - Can transfer fluid & pressure



B

C

Natural fracs – restrict pressure & fluid transfer.

A – hydraulic fracture in dolomite, $W = 0.09''$ or 2.29mm

B – natural fracture in shale, $W = 4 \times 10^{-6}''$ or 108 nm

C – natural fracture in shale, $W = 5 \times 10^{-5}''$ or 1.3 μm

Bridging starts w/ particles $1/3^{\text{rd}}$ to $1/7^{\text{th}}$ the width of the fracture.

Comparative Particle Size:		
U.S. Mesh	Inches	Microns
10	0.0787	2000
12	0.0661	1680
14	0.0555	1410
16	0.0469	1190
18	0.0394	1000
20	0.0331	841
25	0.0280	707
30	.0232	595
35	.0197	500
40	.0165	420
45	.0138	364
50	.0117	297
60	.0098	250
70	.0083	210
80	.0070	177
100	.0059	149
120	.0049	125
140	.0041	105
170	.0035	88
200	.0029	74
230	.0024	63
270	.0021	53
325	.0017	44
400	.0015	37
550	.00099	25
625	.00079	20
1250	.000394	10
1750	.000315	8
2500	.000197	5
5000	.000099	2.5
12000	.0000394	1


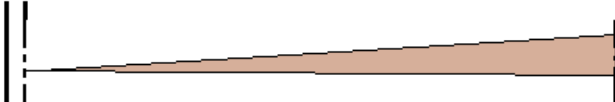
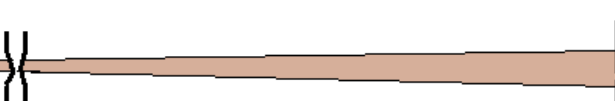
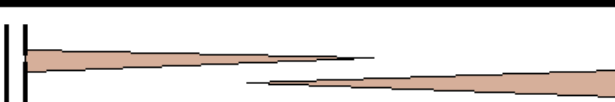
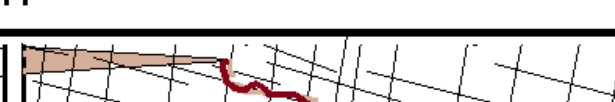


40/70
 100
 Mesh

Source: Universal Filters, Inc.

Natural Fracs 4 to 5 orders of magnitude more narrow than hydraulic fractures

Frac Intersection can be damaging or not, and long term or short.

Visualization & Reaction Estimations of Some Types of Fracture Driven Interactions (FDI)

	FDI Type	Impact Level	Short or Long Term	Est. Casing Damage	Est. Prod. Damage	Monitor Response
	Tip-to-Tip	Minor	Short	No	No	Brief press rise during frac. Closes fast
	Frac into open perfs	Possible Burst	Long	High Risk	High/fill Risk	Transfer of liquid & Proppant Blockage Risk
	Frac crosses wellbore-No entry	Possible Collapse	None?	High Risk	High Risk	Collapse if Passive well not Loaded or if well has corrosion/damage
	Fracture Shadowing-No Entry	Low/none	None	Low Risk	Low Risk	Pressure rise in passive well of less than 20 psi (rock-to-rock stress) Press. disappears after frac.
	Thru N. Frac during frac	Low	Short	Low Risk	Low Risk	N. Fracs close quickly. Very similar to naturally existing connections across parts of shales before frac.
	Skip a well & hit another Thru N. Fracs	Low to Med.	Short	Low/Med. Risk	Low Risk	May or may not damage skipped well. Loading wells will lower damage risk
	Skip a well with long Planar Frac	Medium to High	Long	High Risk	Mod. Risk	May or may not damage skipped well. High risk if not loaded for BHP of of Active well frac.

Bottom Hole Pressure – Frac Stages

If direct communication is established frac-to-offset –well-perfs:

Will BHP be enough to create a burst (or crush) in the passive well?

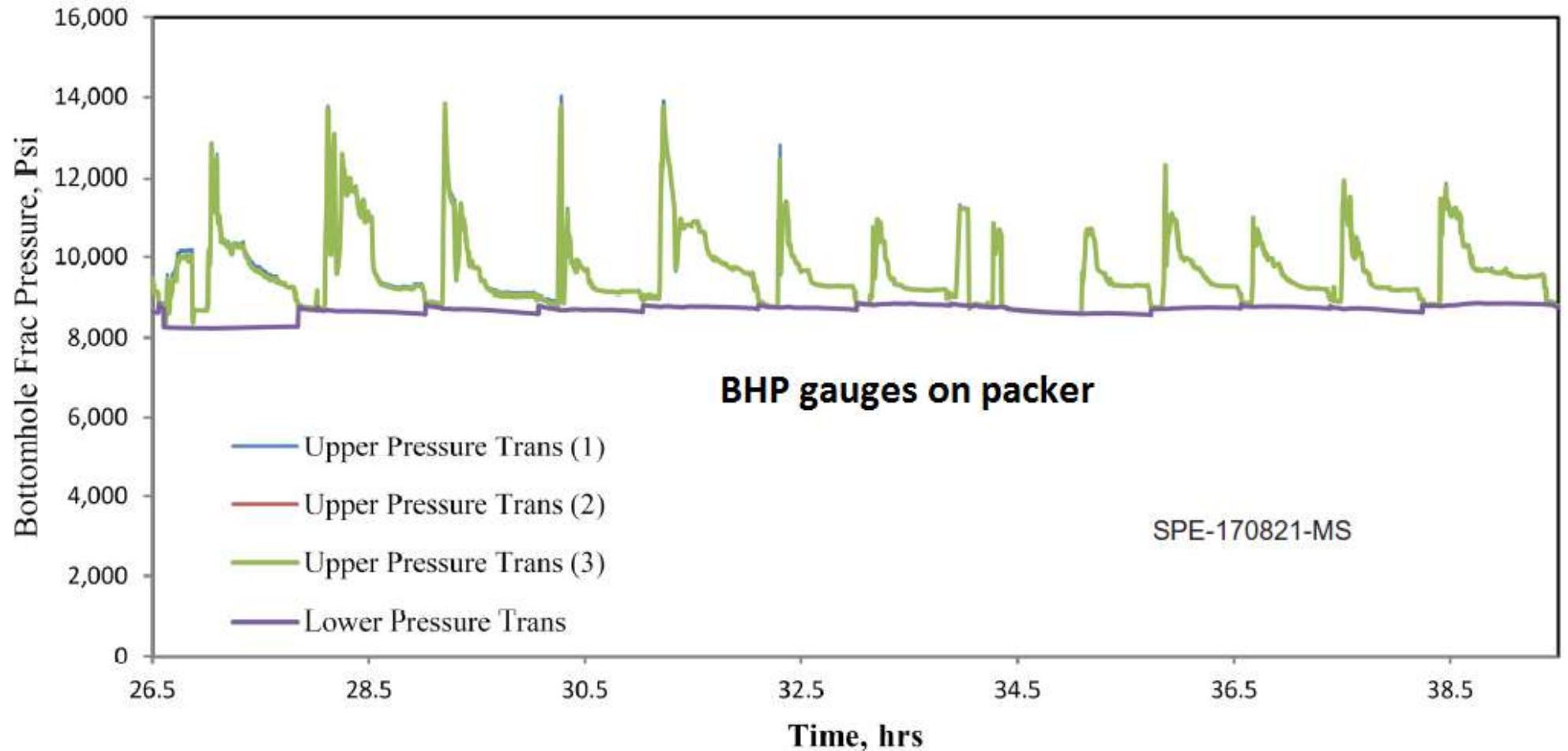
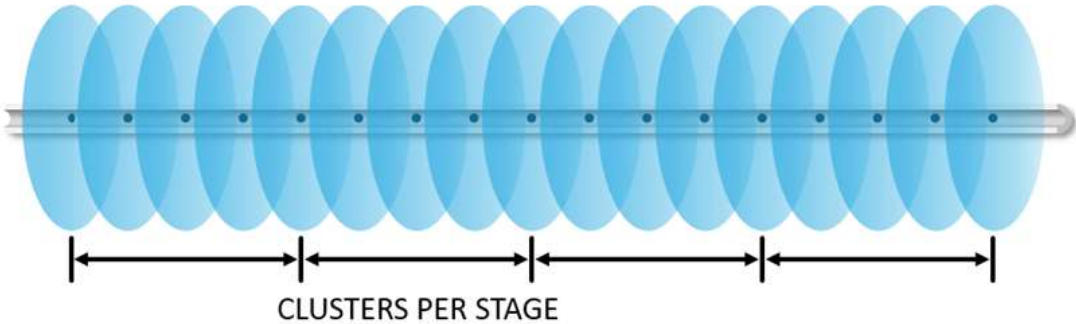


Figure 9—gauged BHFP for stages 12 to 29

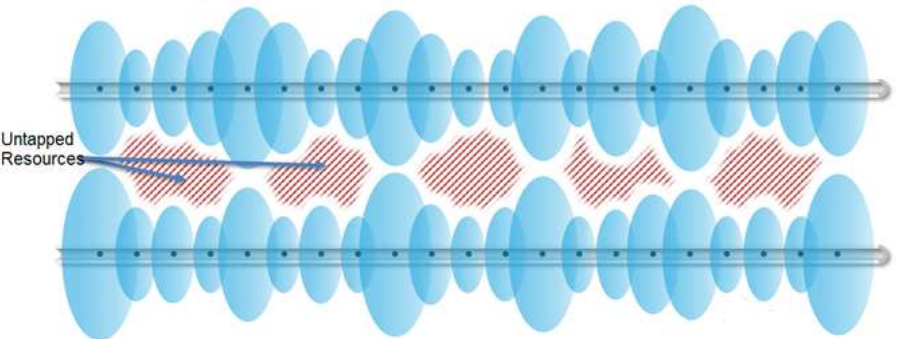
Stress Interference in closely spaced fractures: do they really grow as intended?

Ideal Frac Spacing and Development

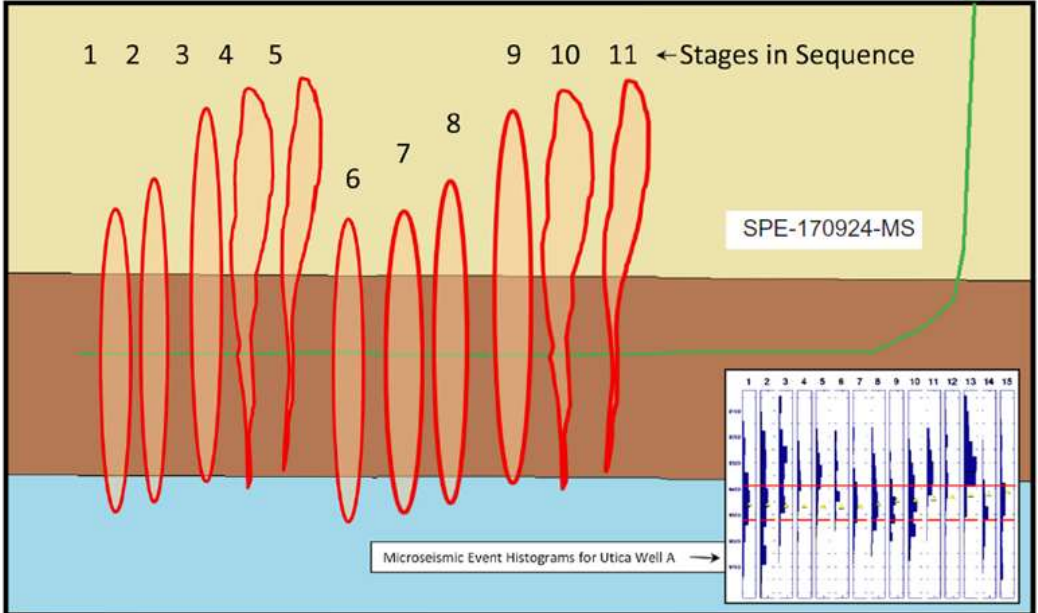


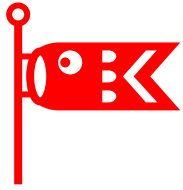
OR...

Reality? - Indication of uneven cluster growth



Or, does close frac spacing push fractures out of zone





Rock Fabric

(from Neal Nagel, “It’s the Rock Fabric, Stupid !” Geomechanics for Unconventionals Series, 2019),

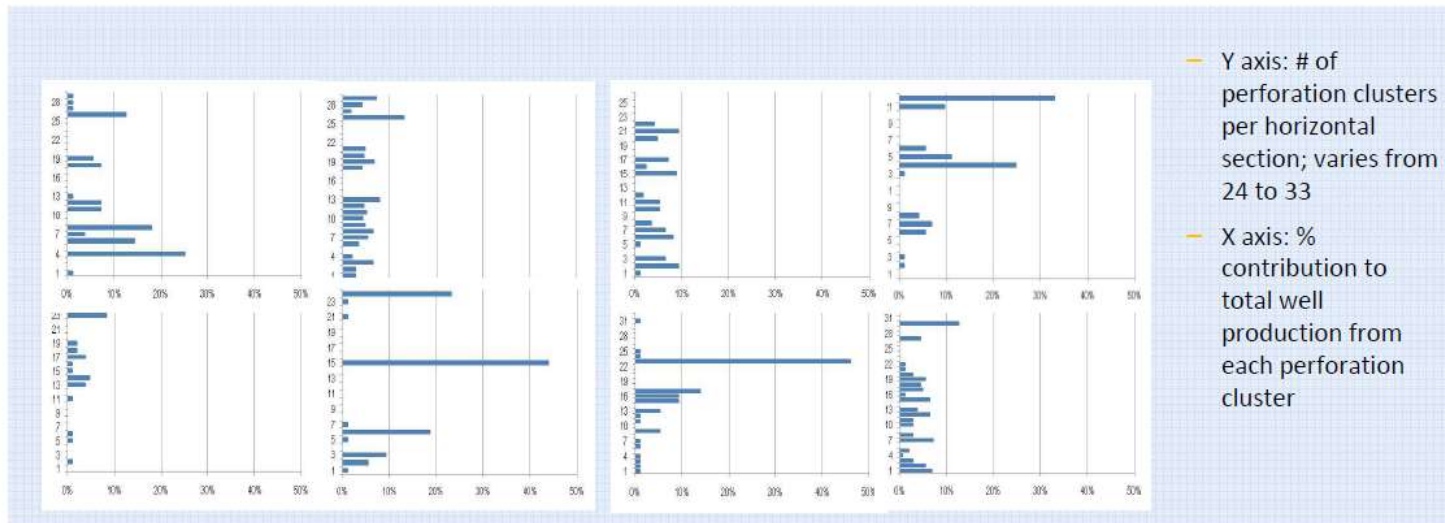
- Rock Fabric is the variation in mechanical properties, vertically and laterally, for a specific rock, especially the variation in strength and potential for time-dependent deformation.
- For Unconventionals, rock fabric is dominated by “weak-strength features” (e.g., natural fractures, bedding planes and layers).

The 4th dimension in rock fabric is TIME, the 5th is pressure depletion.

Are all these closely spaced fracs paying for themselves?

At the end of the day, well performance analysis of US shale wells shows that about 50% of perforation clusters do not produce gas

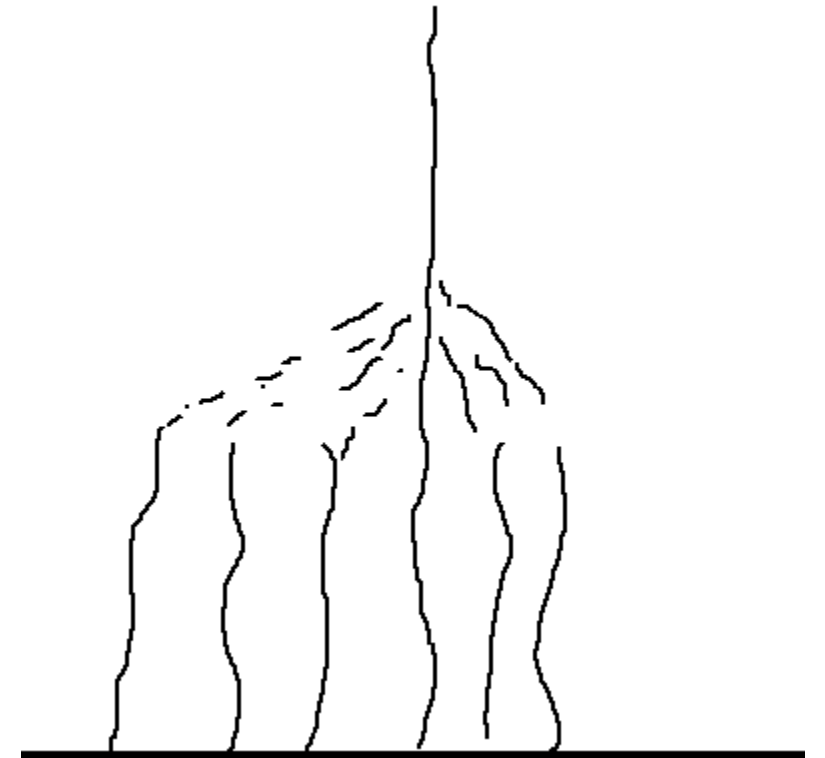
Sample of production logs from producing horizontal wells in one development by single operator using same technology:



Source Francois Dubost

Therefore a well characterized reservoir and completion is the first step in understanding what we may look for, for remedial plans and improvements in ultimate recoveries

Are multiple fracs coming together to make one LONG planar frac?



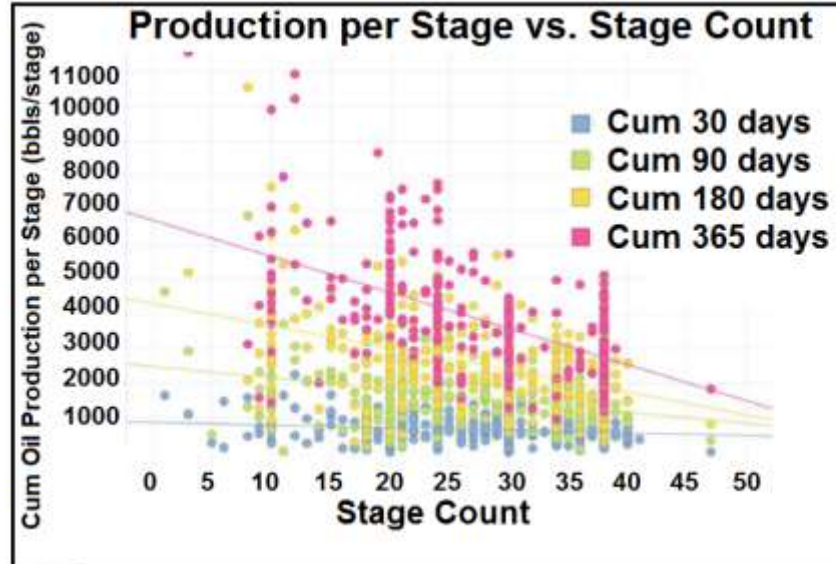
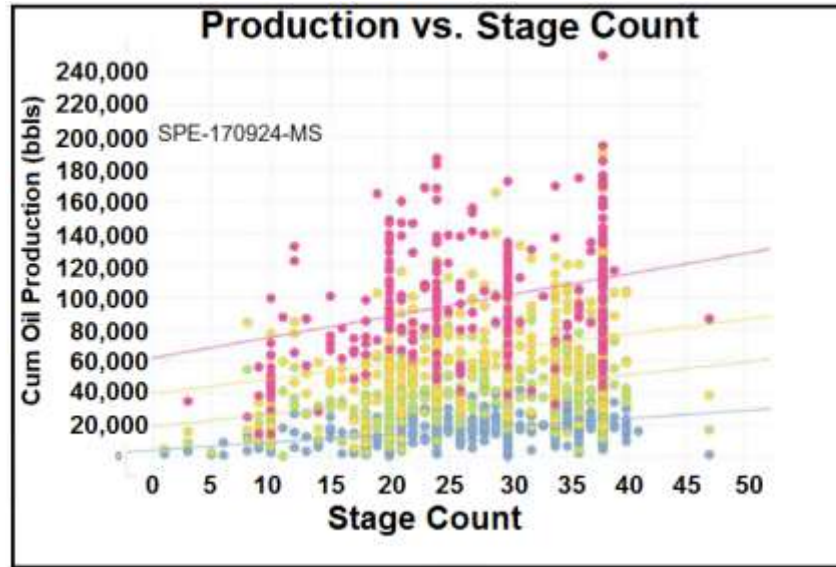
Does adding more frac stages really help?

Is it a case of diminishing returns?

Production vs. stage count

and

Production per stage vs stage count.



Bakken Production per well after 30, 90, 180 & 365 days vs. stage count (above) and production per stage vs. stage count (below).

Data from NDIC public database & graphs courtesy of Neil Decker, Hess Bakken Team.

Production performance does not scale up in simple increments when adding closely spaced fractures.

Rock Fabric : Geologic and Geo-Mechanical Factors Below the Source Rock May Impact the Productivity

SPE 163846

2 wells – first ten days

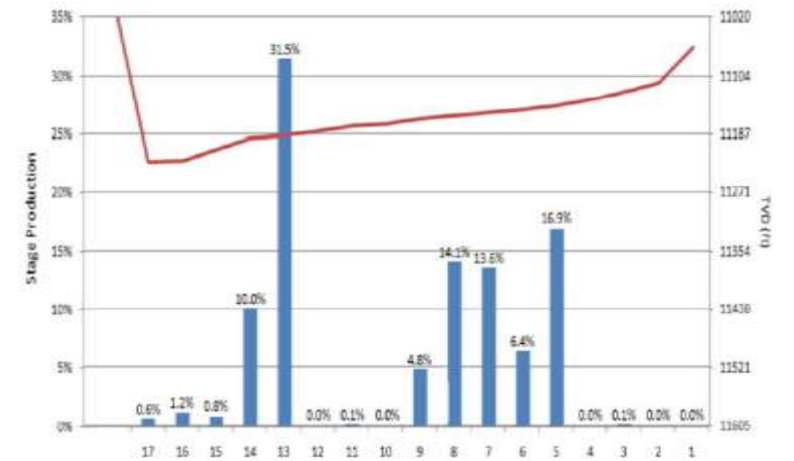
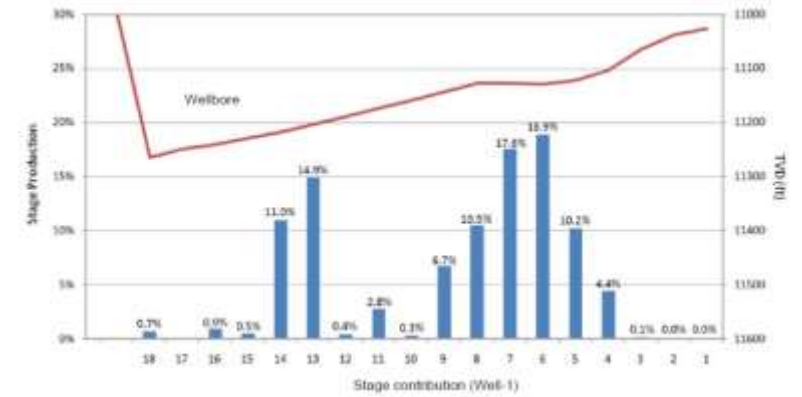
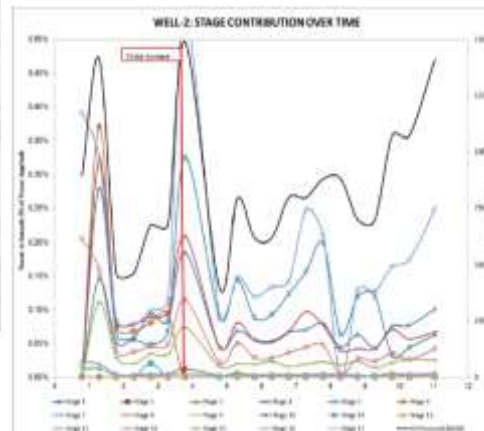
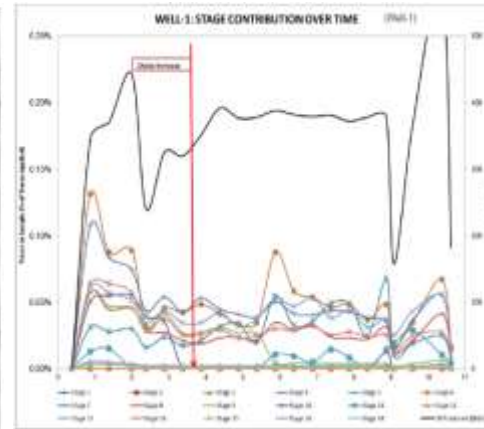
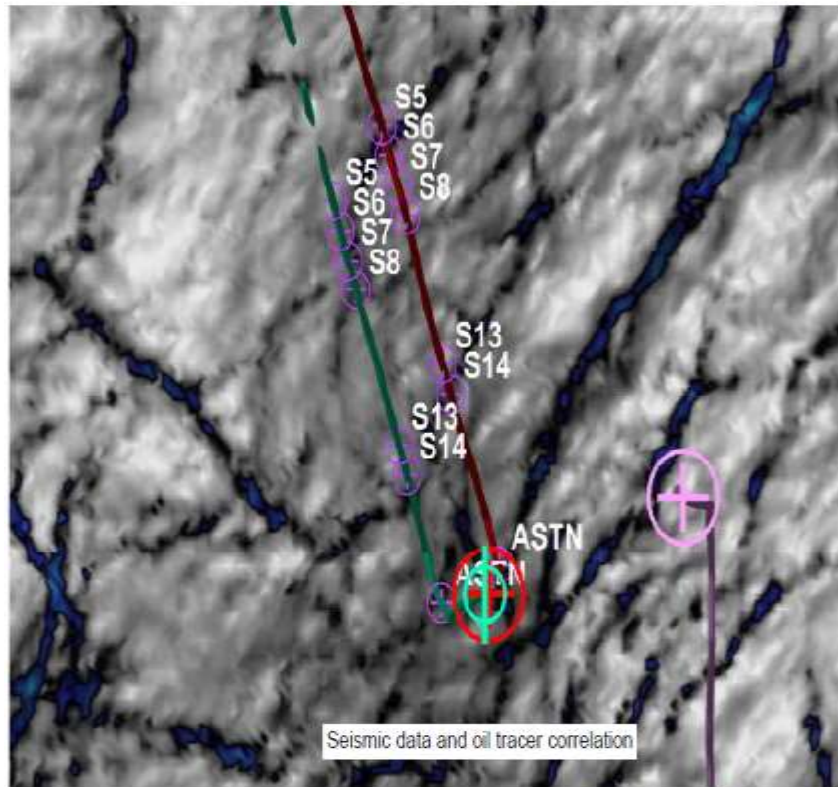
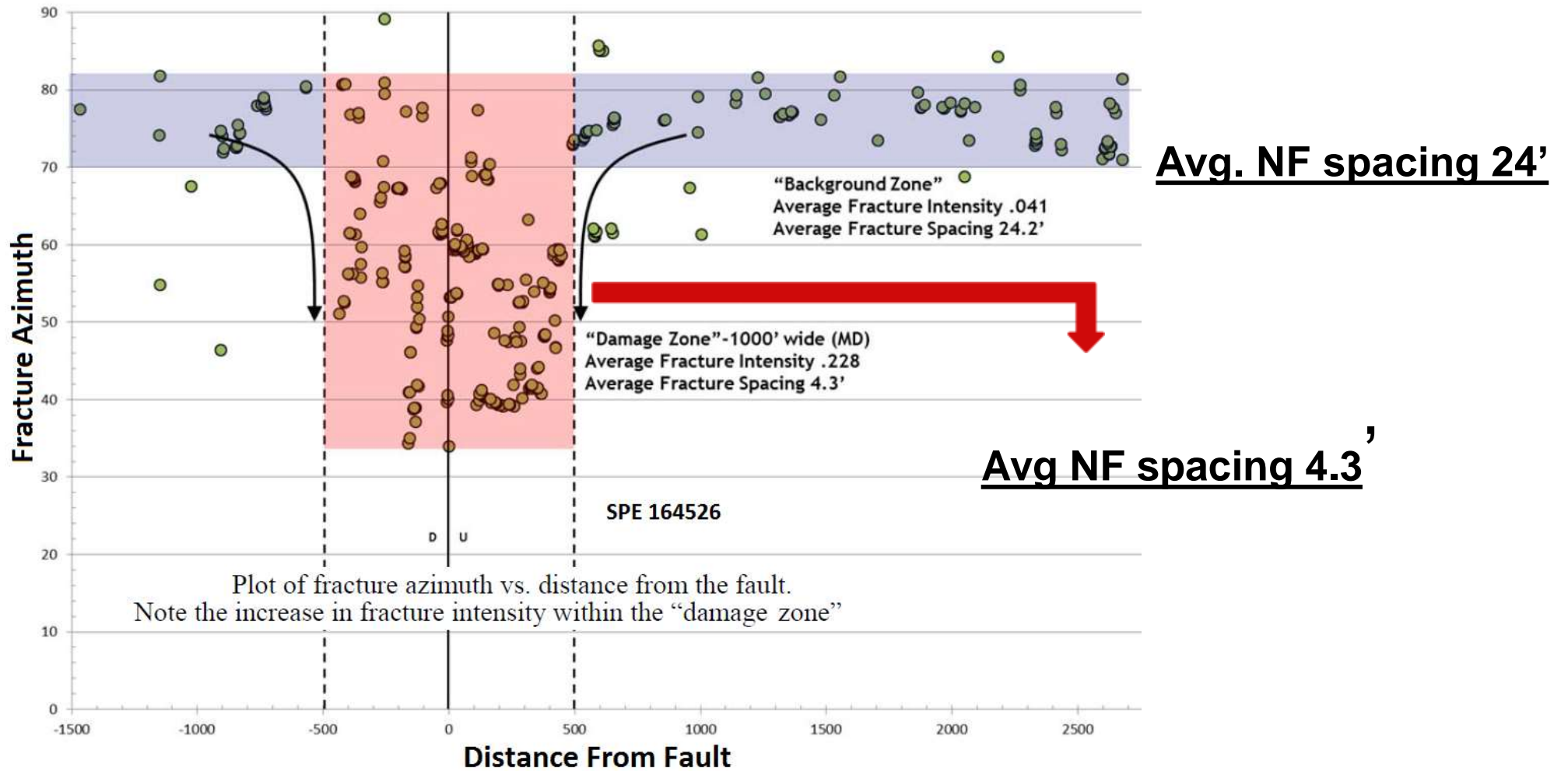



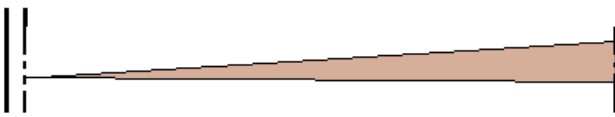
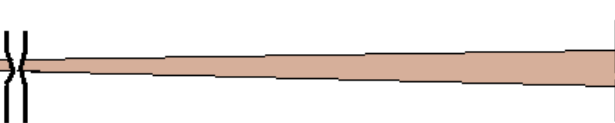
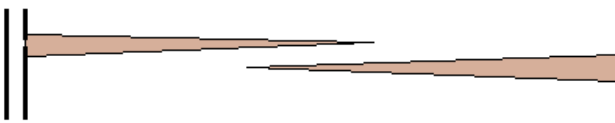
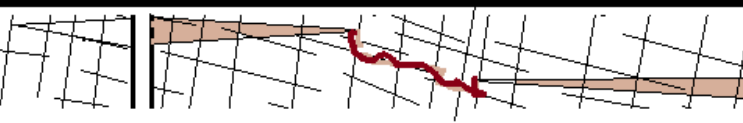
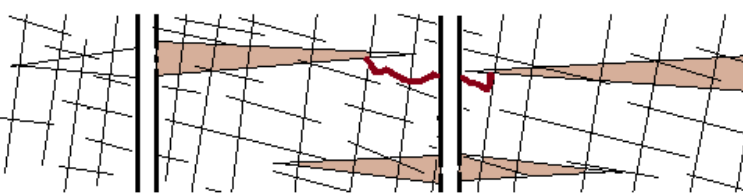
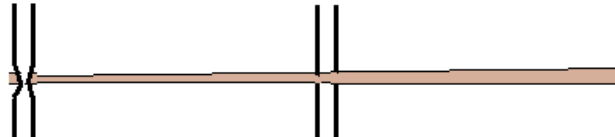
Figure 6. Stage contribution (Well-2)

Rock Fabric is Dynamic: A Five-Dimensional Variable?



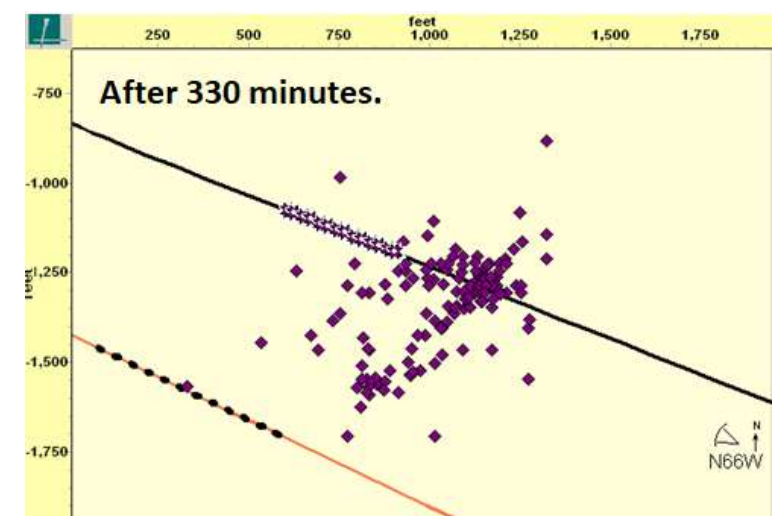
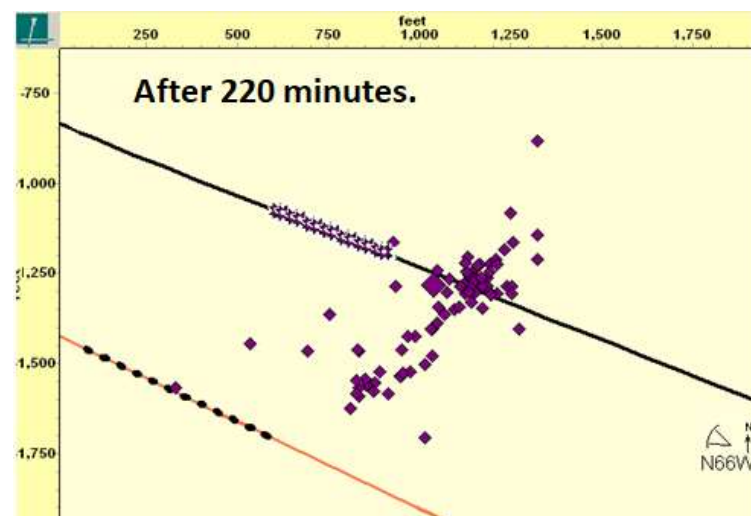
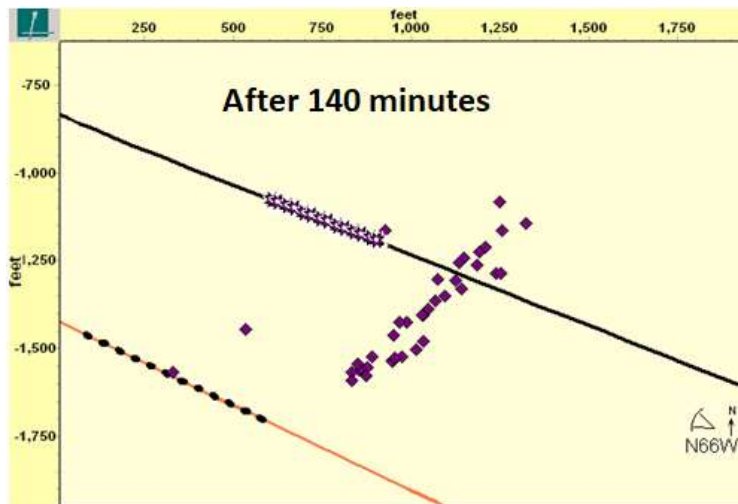
Numerous Types of FDI – some damaging – some not.

Visualization & Reaction Estimations of Some Types of Fracture Driven Interactions (FDI)

	FDI Type	Impact Level	Short or Long Term	Est. Casing Damage	Est. Prod. Damage	Monitor Response
	Tip-to-Tip	Minor	Short	No	No	Brief press rise during frac. Closes fast
	Frac into open perms	Possible Burst	Long	High Risk	High/fill Risk	Transfer of liquid & Proppant Blockage Risk
	Frac crosses wellbore-No entry	Possible Collapse	None?	High Risk	High Risk	Collapse if Passive well not Loaded or if well has corrosion/damage
	Fracture Shadowing-No Entry	Low/none	None	Low Risk	Low Risk	Pressure rise in passive well of less than 20 psi (rock-to-rock stress) Press. disappears after frac.
	Thru N. Frac during frac	Low	Short	Low Risk	Low Risk	N. Fracs close quickly. Very similar to naturally existing connections across parts of shales before frac.
	Skip a well & hit another Thru N. Fracs	Low to Med.	Short	Low/Med. Risk	Low Risk	May or may not damage skipped well. Loading wells will lower damage risk
	Skip a well with long Planar Frac	Medium to High	Long	High Risk	Mod. Risk	May or may not damage skipped well. High risk if not loaded for BHP of of Active well frac.

Two parts of fracture growth in some shales: Planar to start & complex after first Tip screenout

- Planar fracturing dominates frac growth but natural fractures are the flow path in ultra-low permeability matrix reservoirs.
- Natural fractures can be opened – in some reservoirs.....



Some Driver Factors involved in FDI

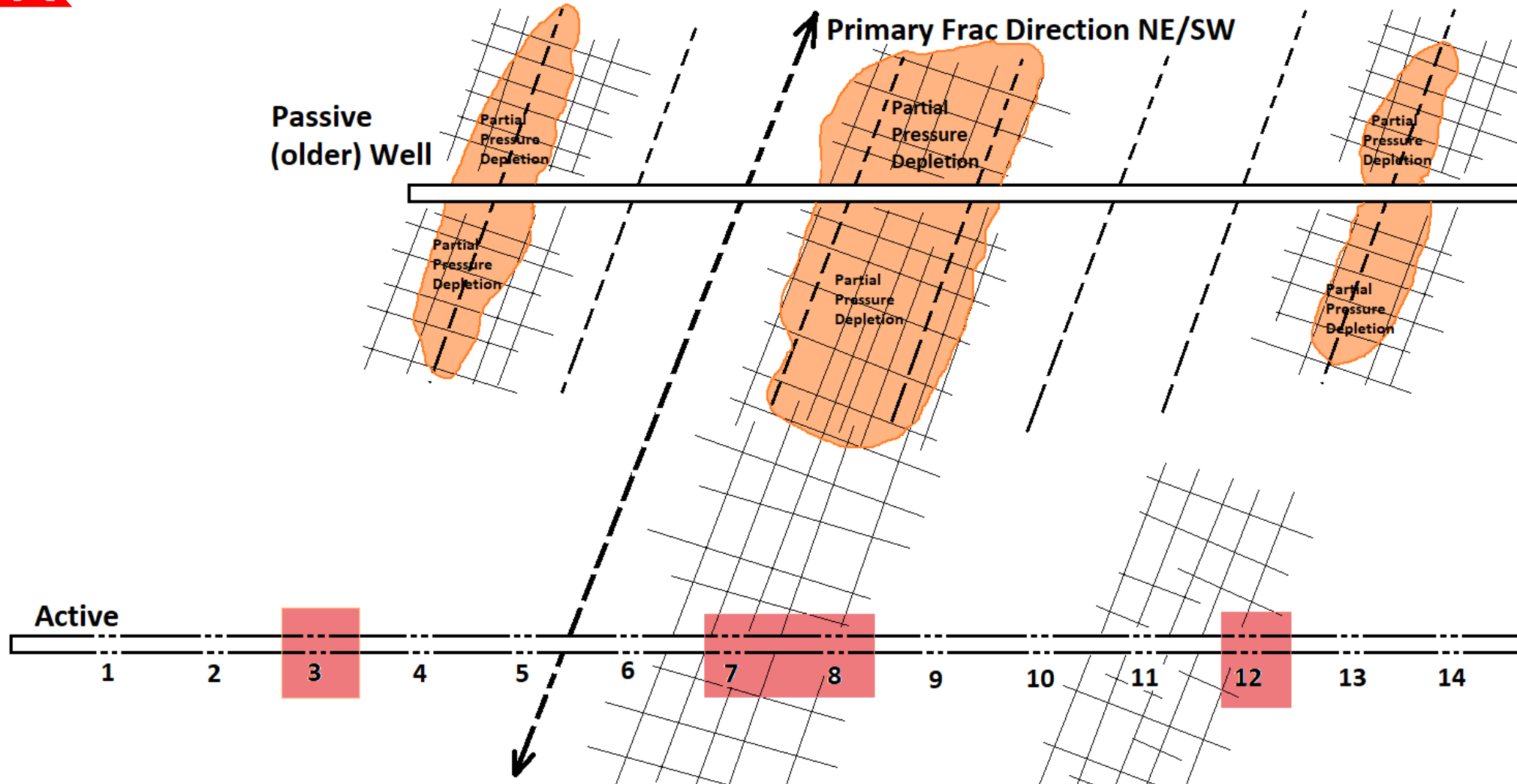
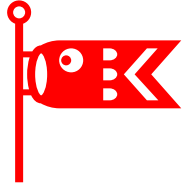
Geologic & Geo-mechanical

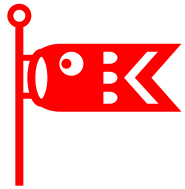
- Pressure Depletion in Offset
- Insitu Stress (off-balance?)
- Geological (faults, layers, tilt)
- Rock Fabric (including nat. fracs)
- Barriers
- Pressure differences
- Frac Direction
- Mineralogy (brittle or ductile)
- Frac Inclination (well-to-well)

Design & Application

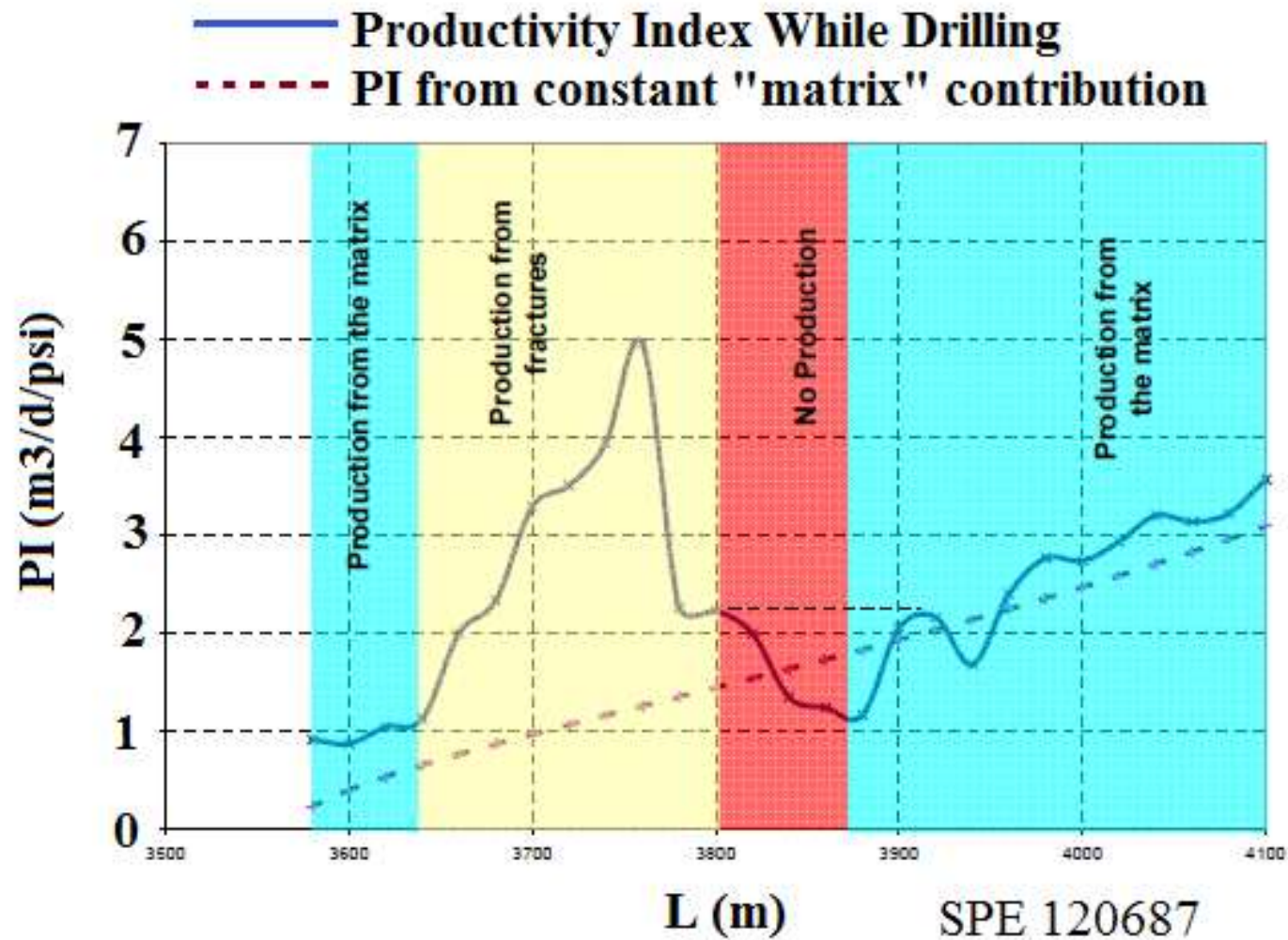
- Completion type (single or clusters)
- Cement Isolation Quality
- Well Spacing & Frac Spacing
- Frac Design (Type, Vol., Rate, Prop)
- Ability/Inability to Change Frac O.T.F.
- Simultaneous or Sequential (Time?)
- Rate Application Speed (Step Up?)
- Diversion Quality & Efficiency
- FDI Potential Recognition
(before, during & after fracturing)

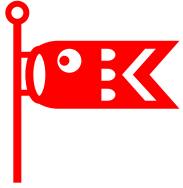
Areas of direct concern in frac-to-depleted pressure area



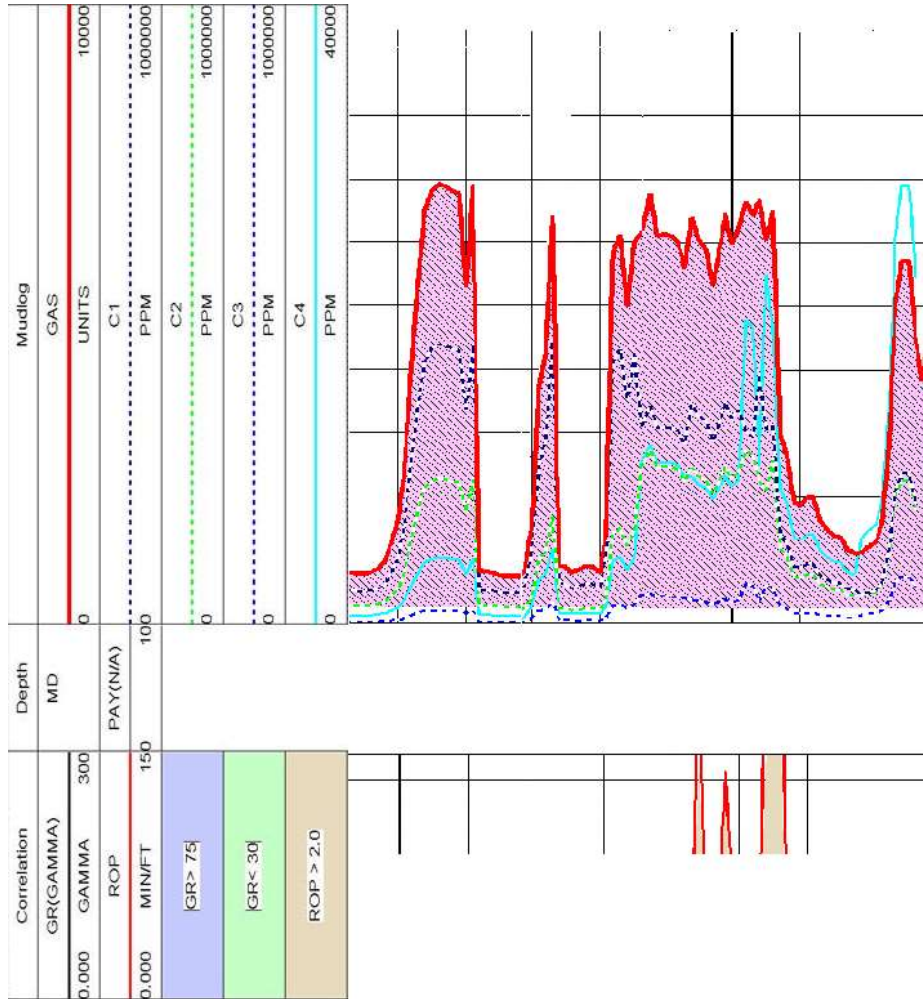


Productivity Index Along the Lateral (taken during underbalanced drilling)



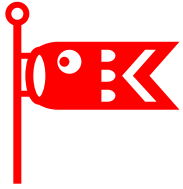


Look for the Gas Shows



- Gas Show
 - Quantity
 - Ratio of gasses
 - Corresponding GR
- Other logs (CNL, Density) to help assess TOC
- Density for Brittleness
- Resistivity for water saturation and salinity
- ROP (rate of penetration)
- Is it a hot shale or a natural fracture?

Is the objective to align the perf clusters with natural fractures?



Fracture Interactions, Poro-elastic Response (Frac Shadowing) SPE 189853-MS

MONITORING TECHNOLOGY PRESENTATION AND FRACTURE INTERACTION STUDY, Michael F Rainbolt, P.E.

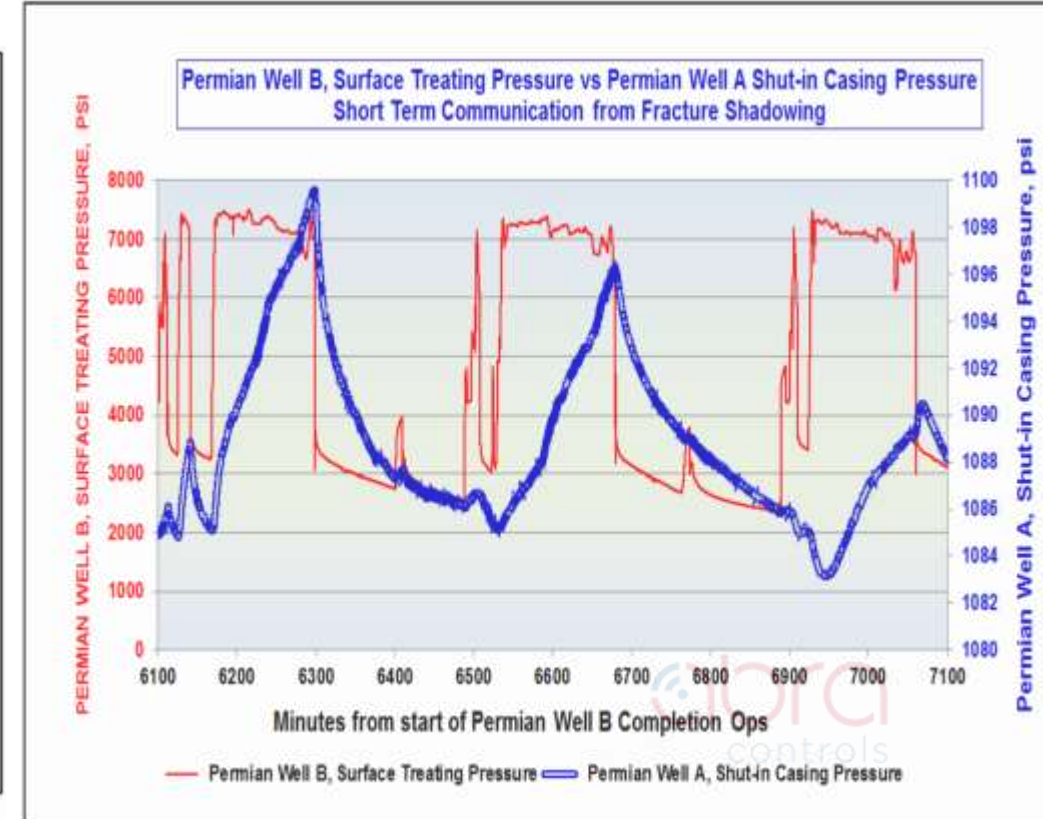
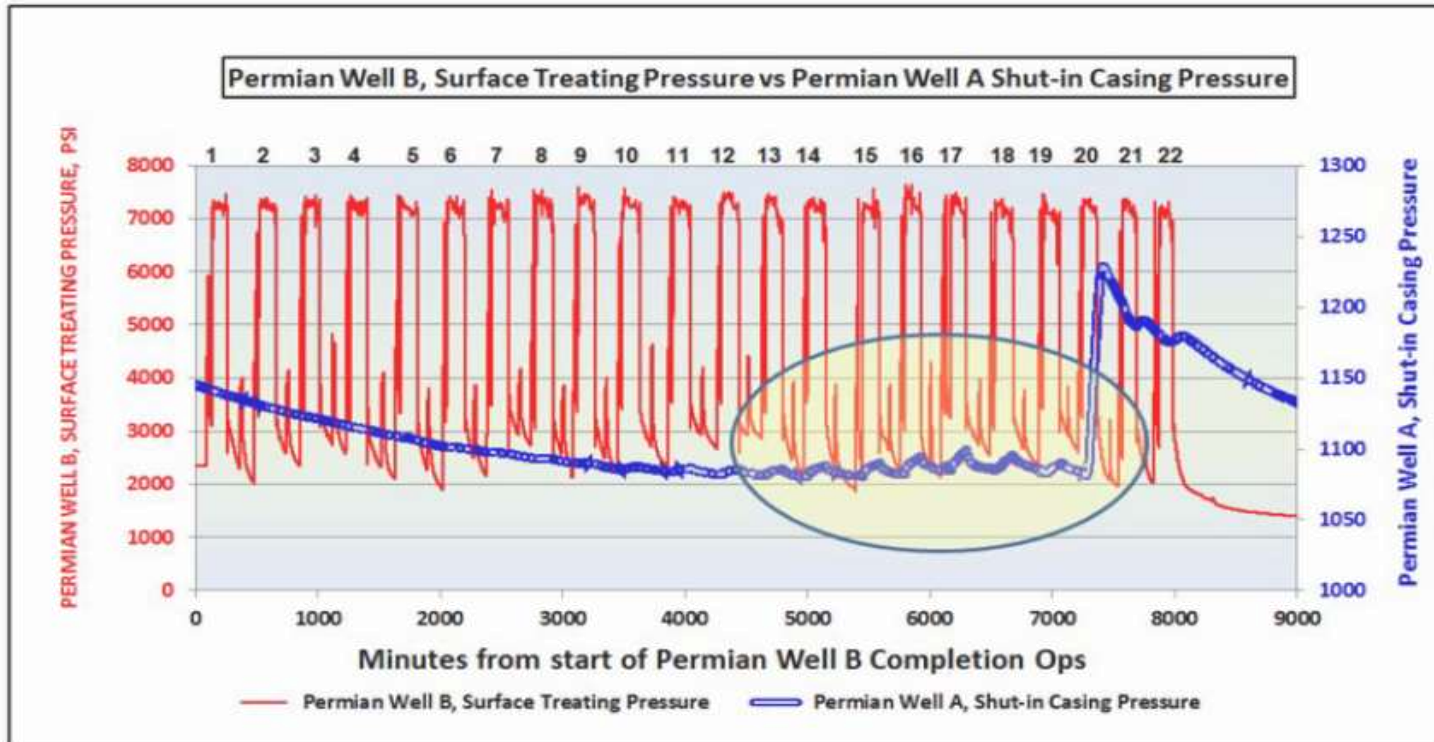


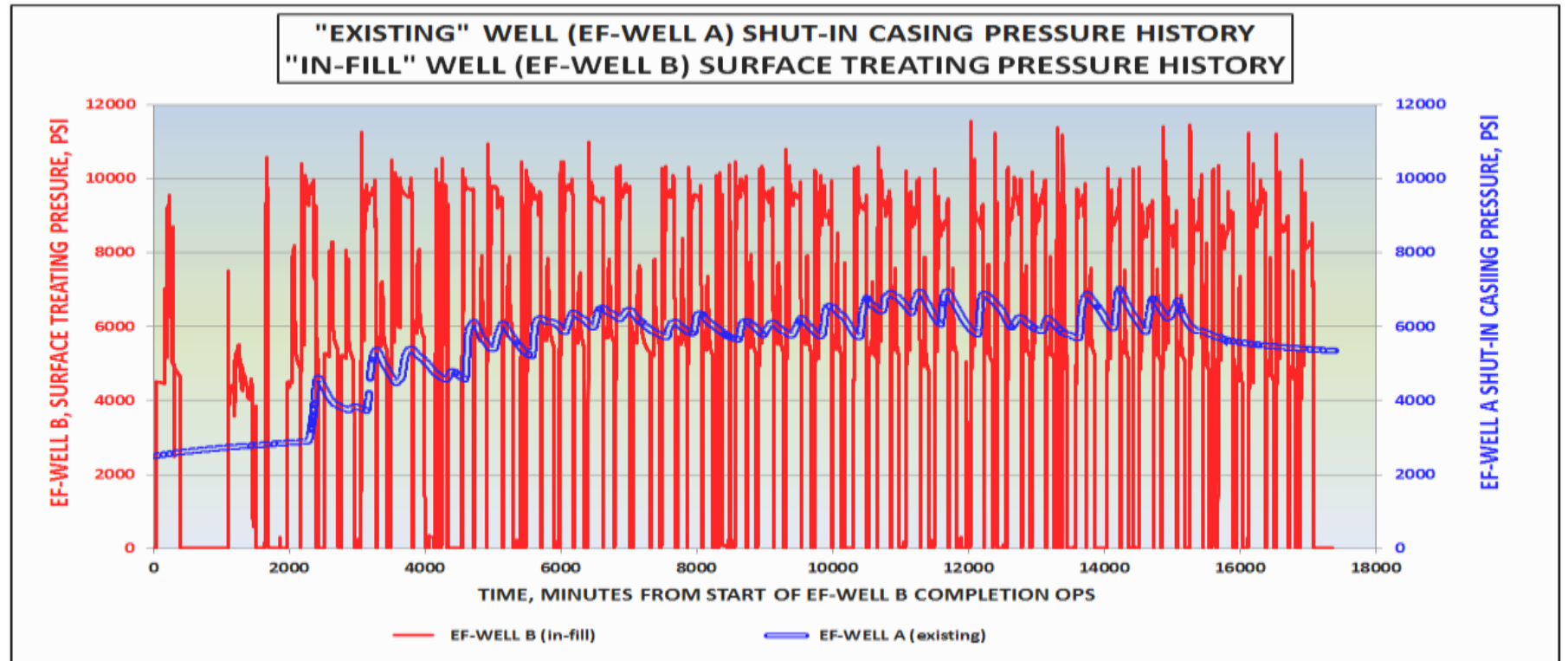
Figure 29—Case Study IV, Fracture Shadowing Transitioning to Fracture-to-Fracture Intersection

Fracture Interactions, Fracture-to-Fracture Connections - SPE 187192-MS

These two wells had a more permeable intersection, but the passive well pressures were about 4kpsi lower and several frac stages did not appear at the passive well.

Why?

1. The interaction is stronger than a fracture shadowing event – some connections made.
2. The passive well is shorter than the active well and not quite parallel.



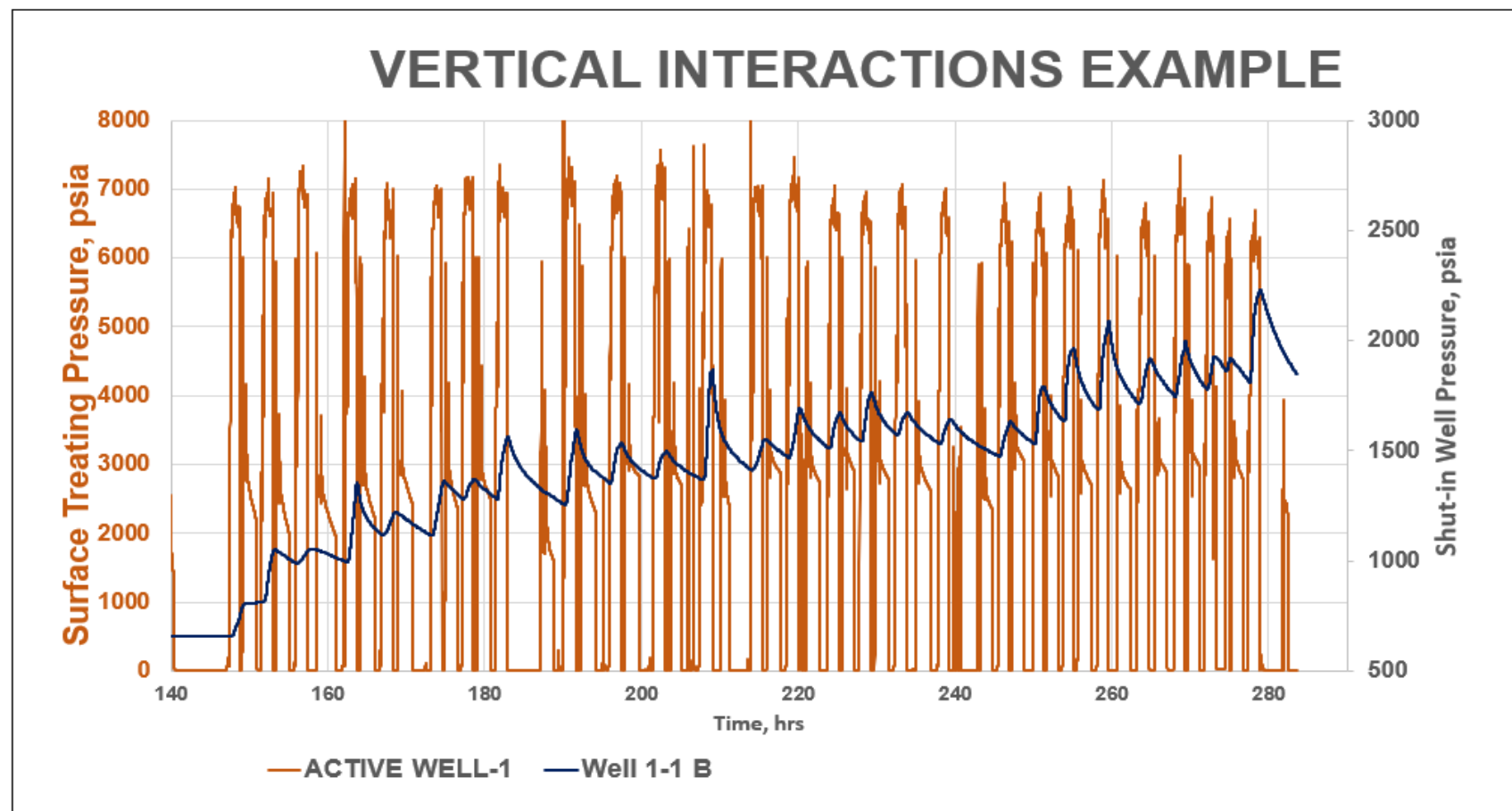
MONITORING TECHNOLOGY PRESENTATION AND FRACTURE INTERACTION STUDY, Michael F Rainbolt, P.E.

WELL-TO-WELL VERTICAL GROWTH INTERACTION ACTIVE WELL / PASSIVE WELL EXAMPLE

Active well STP (left Y axis) may range to 8kpsi but pressure recorded at passive (shut-in) well is less than 2500 psi.

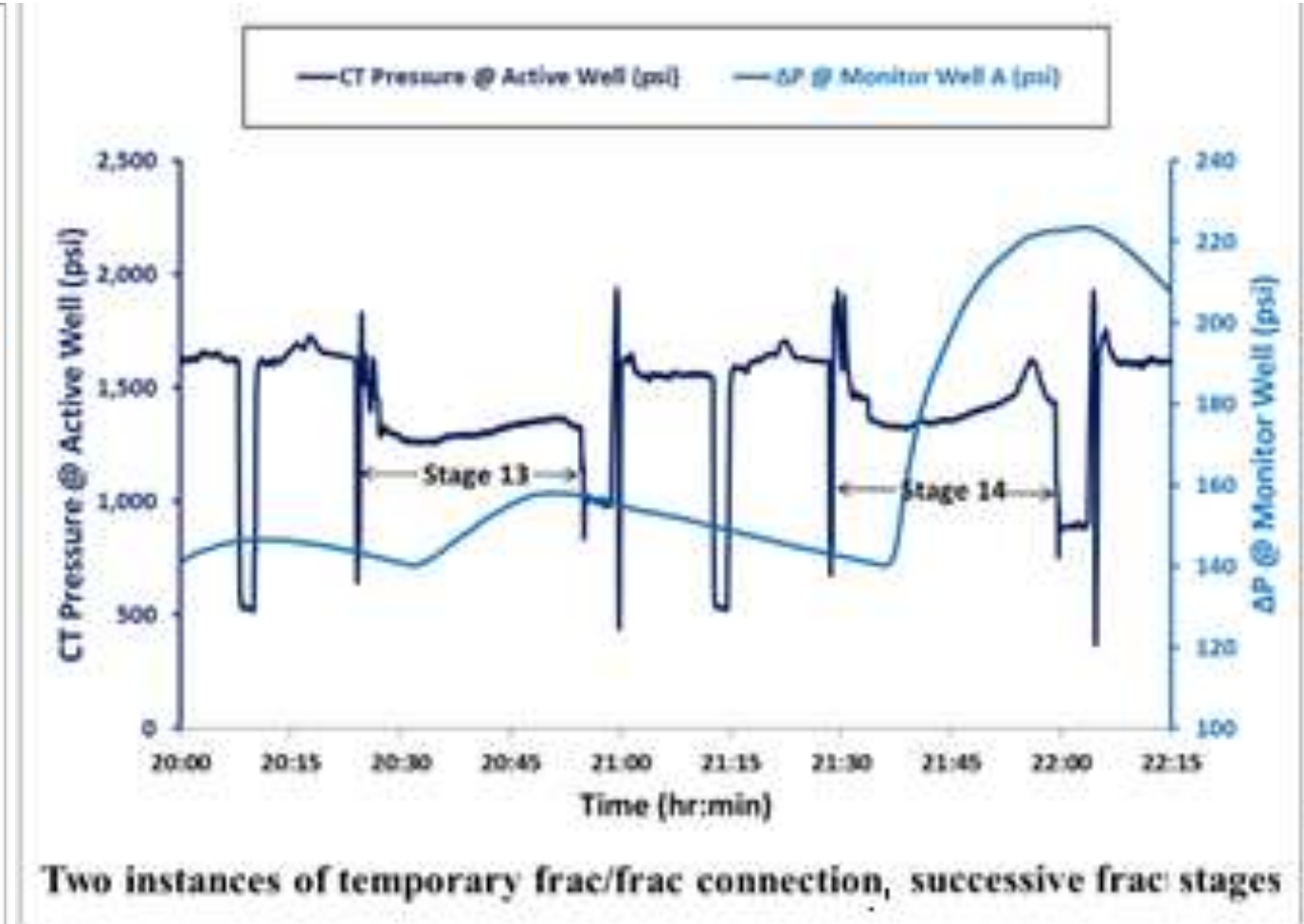
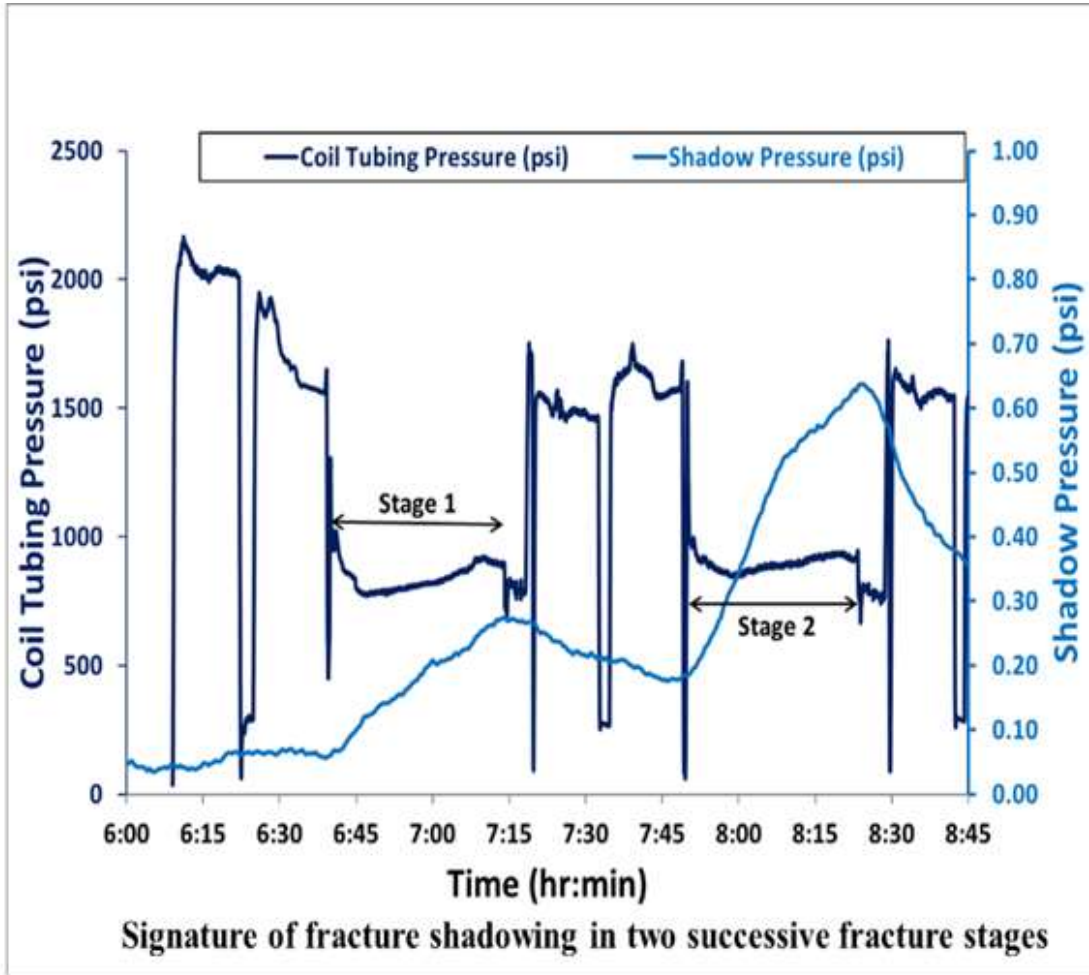
Although the frac intersection does not support a high flow rate between wells, the pressure inflection with almost every frac is picked up in the passive (shut-in) well.

Frac at 185 & 245 minutes do not connect. Why?



Fracture Shadowing and Temporary Connection Examples

(Courtesy of Ali Daneshy)



Workflows for FDI Occurrence, Potential for Casing Damage, & Potential for Production Loss

- Specific workflows for particular areas are required.
- The accuracy of data necessary to create these workflows is critical to accuracy of predictions.
- Assumptions:
 - perforations/sleeves placed according to design.
 - closely spaced fracs do not coalesce into a single, long planar frac,
 - orientation follow the design, and
 - geologic unknowns are minimized.

Recovery after a Frac Hit: Chemical Treatments

- Some very successful chemical treatments after a frac
 - Focused on load water recovery (more popular in conventional wells?)
 - Focused on improving the flow passage
 - Finite volume of chemical only lasts a finite time.
 - Wetting alternation
 - Oil viscosity reduction
 - Obstruction removal or improving flow path is long-lasting
 - Role of acid?

Remediation with a Small Volume Acid/Chemical Treatment (Both Frac Hits - Scoop Area)

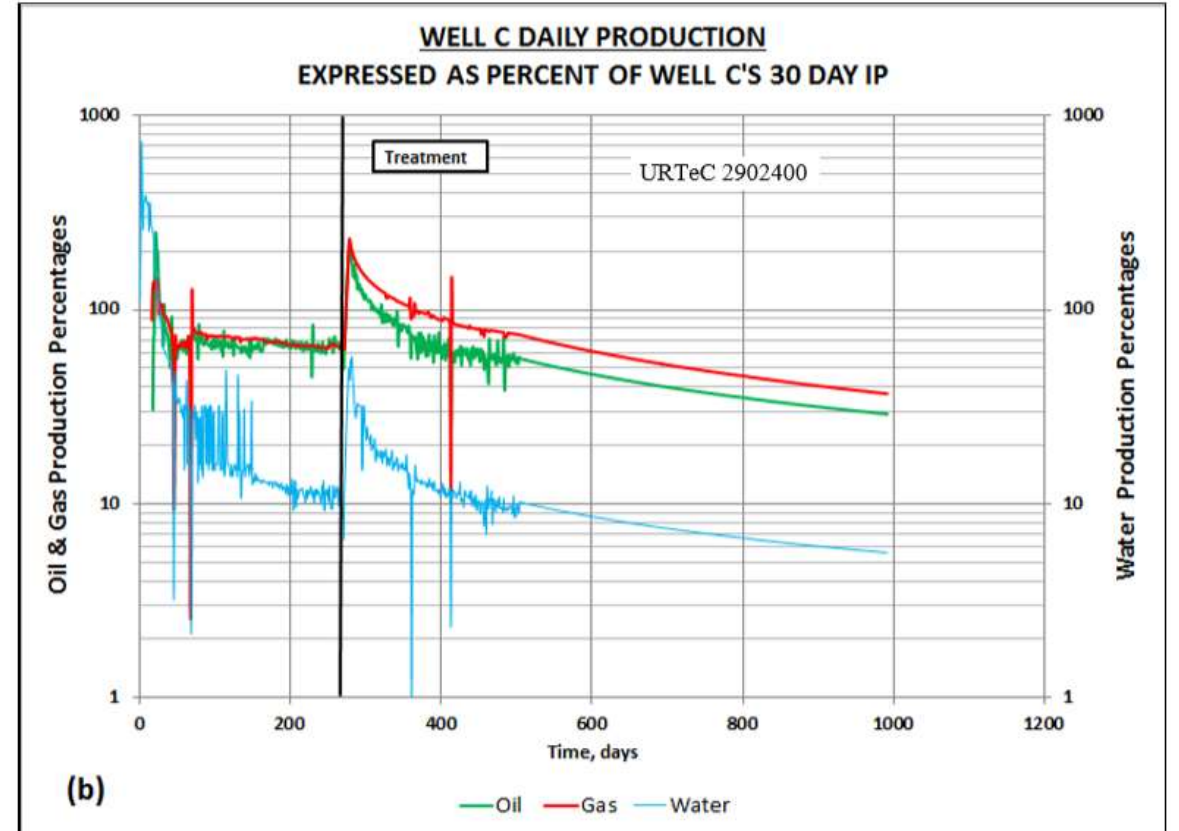
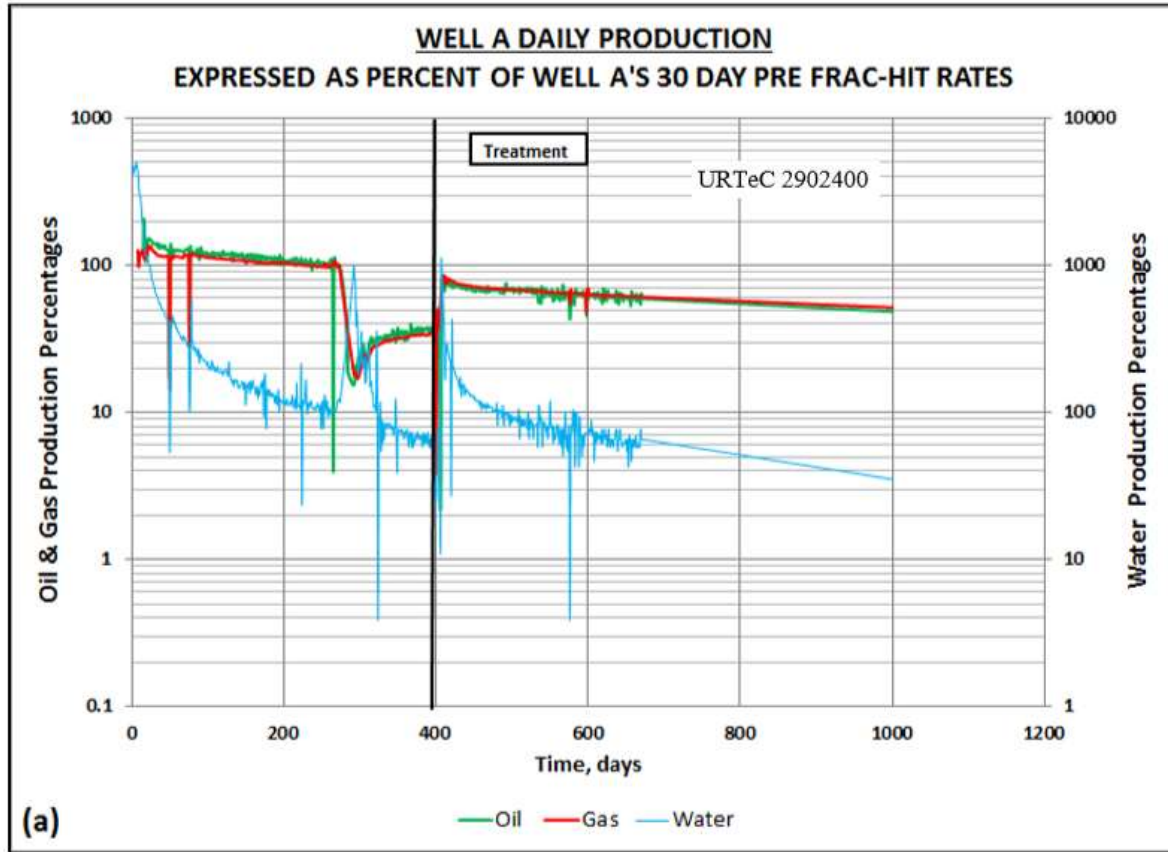


Fig. 9 - Daily production data as % of 30-day IP. (a) Well D production data (b) Well C production data.

Natural recovery time shortened by 2 years in Well A

Some Driver Factors involved in FDI

Geologic & Geomechanical

- **Pressure Depletion in Offset**
- **Insitu Stress (off-balance?)**
- **Geological (faults, layers, tilt)**
- **Rock Fabric (including nat. fracs)**
- **Barriers**
- **Pressure differences**
- **Frac Direction**
- **Mineralogy (brittle or ductile)**
- **Frac Inclination (well-to-well)**

Design & Application

- **Completion type (single or clusters)**
- **Cement Isolation Quality**
- **Well Spacing & Frac Spacing**
- **Frac Design (Type, Vol., Rate, Prop)**
- **Ability/Inability to Change Frac O.T.F.**
- **Simultaneous or Sequential (Time?)**
- **Rate Application Speed (Step Up?)**
- **Diversion Quality & Efficiency**
- **FDI Potential Recognition
(before, during & after fracturing)**

Some Minimization/Control Methods For FDI

- **Active**

- Monitor Passive Wells (to few psi)
- React to Monitors, Alter Frac O.T.F.
- Sequential/Simul Frac (new wells)
- Refrac Old Wells & Hold Pressure
- Gas Pressuring of Offset Wells
- Pressure Wall (Pre-Loading)
- Step-Up Frac Rate (+10 bpm incr.)

- **Passive**

- Shut-ins (limited)
- “Pressure Walls”
- Recognize Stress and Rock Barriers
- Well/Frac Design
 - Old perfs not in new frac plane
 - Stagger vol. in depleted offsets
 - Identify local FDI drivers
 - Wider well separation (?)

NO one-size-fits-all plan =>

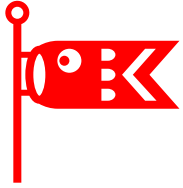
1. Identify high risk conditions and wells.
2. Formulate passive and active control plans.

Damage Minimization Methods

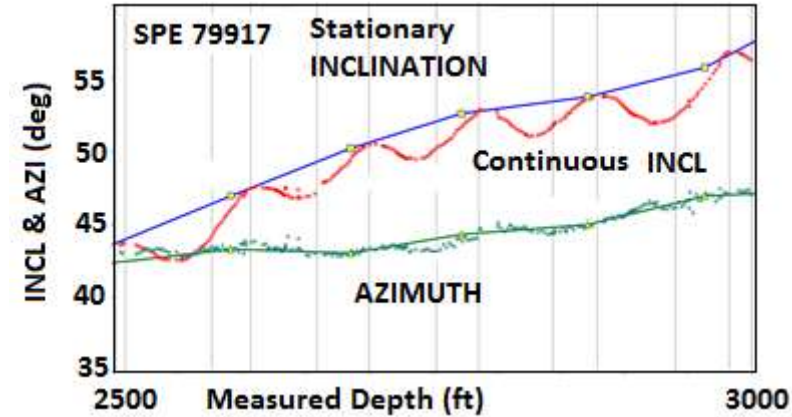
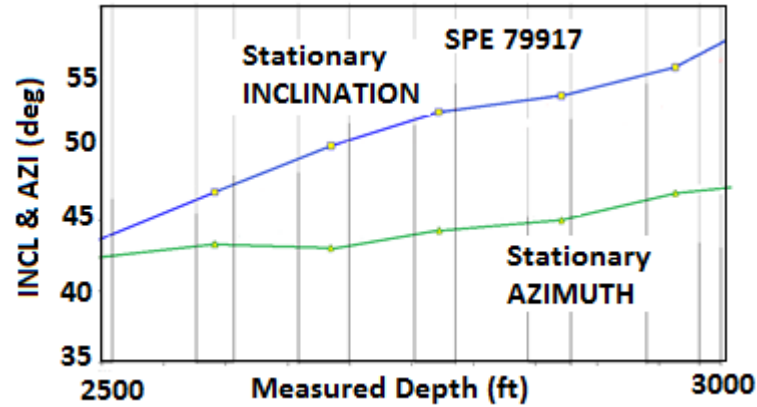
- **Methods**
 - **Building Pressure Walls (injection, refracturing, simultaneous fracs)**
 - **Monitor and actively control fracture**
 - **Shutting in - short term** – sporadically successful, with many noted failures.
 - **Shutting in – long term** – more successful but difficult and expensive.
 - **Leaving the well open** (continuing flow) – unpredictable results.
 - **Loading the well with water or nitrogen over water** (higher pressurized).
 - **Fracturing both wells** – higher probability of success. Can be done sequentially or simultaneously
 - **Old wells** - check success based on timing of treatment. Old wells and old damage is probably not a good candidate for treatment.
- **Conclusions** – not a universal good way to totally prevent a frac hit.

Casing Failures Associated with MFHW

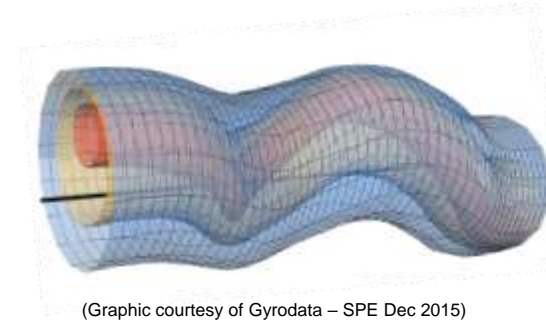
- **Most Common Among Rare (?) Deformation & Failures Associated w/ Fracs**
 - **Drilling/Completion-Driven**
 - Undulating Wellbores => pipe bending & spiraling => enabler for ovaling(?)
 - Torque problems from close casing to wellbore clearances -from rotation (pipe body or couplings)
 - Enabled failures by lack of cement support (isolation of pipe body and coupling leaks)
 - **Frac Driven Intersection Failures (Passive Well)**
 - Deformation (ovaling) and collapse – (higher risk w/ poor cementing practices)
 - Burst (Directly Applied & trapped pressure during fracturing or start-up (worse w/ poor cement)
 - **Fracturing Driven Failures (in the Active Well)**
 - Erosion in the couplings from proppant – below the wellhead
 - Jump-out (at the couplings)
 - Bending forces at the couplings – create pipe body failures within a few pipe diameters of joint
 - Cyclic Application of Pressure (multiple fracs – pipe & couplings?)
 - **Production Related**
 - High rate flow erosion in the couplings
 - Low side channel development in the flow-path over time
 - Usage change (pipe & couplings)



Buckling Failure Points (symptoms & causes)



Causes?
Too much dog leg severity (DLS) – drilling too rapidly, Subsidence, etc.

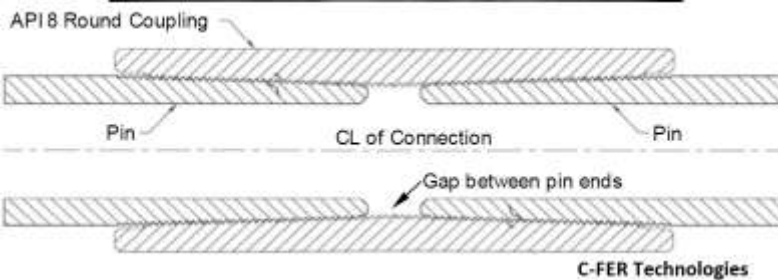
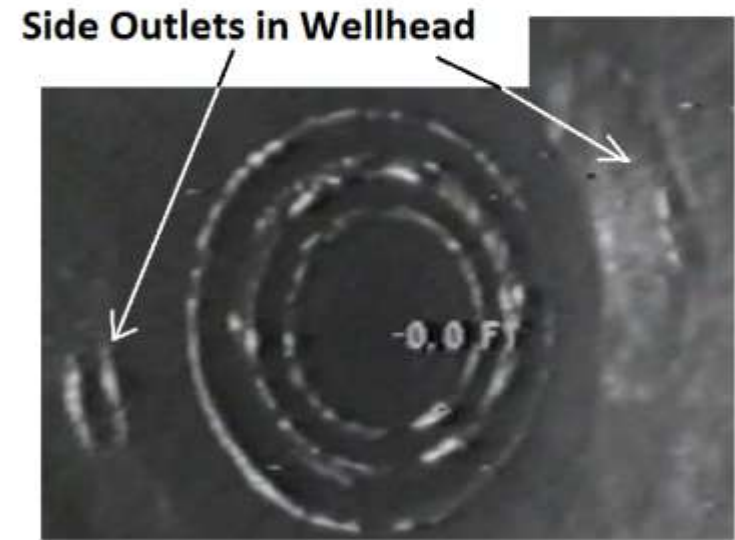
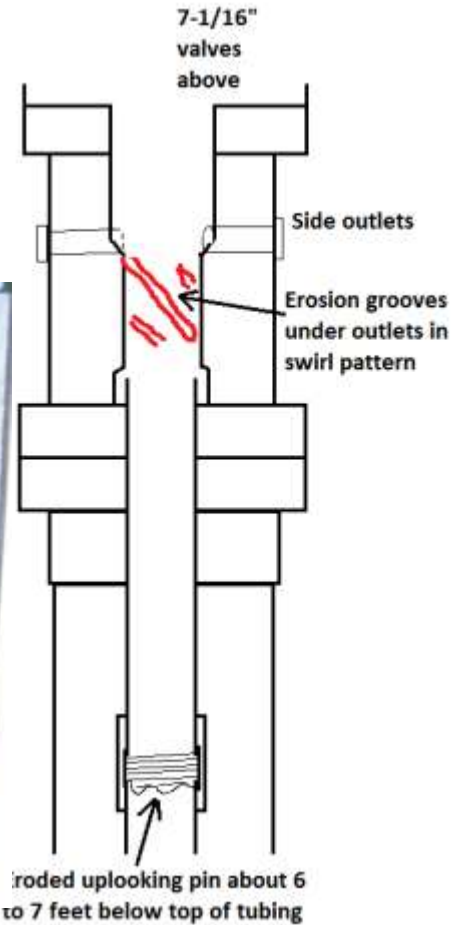
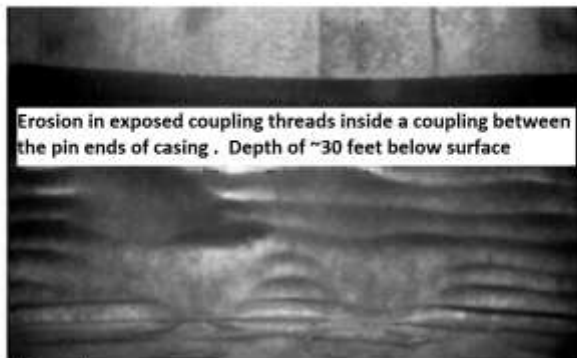


(Graphic courtesy of Gyrodata – SPE Dec 2015)

Source: Rassenfoss, S., "Drilling Wells Ever Faster May Not Be the Measure of Success," SPE JPT

Erosion below wellhead side ports. May lead to mechanical damage in pressure spikes.

Erosion may be most severe after flow path change and higher at shallower depths.



Some FDI Factors in Horizontal Wells – negative, positive, benign

- Rock Fabric is an important influence on FDI, Casing Deformation & Production
- Short & Long Term Tip-to-Tip fracture connections:
 - Fracture connections along same wellbore,
 - Fracture connection to offset wellbore(s),
- Off-Balance Pressure Behavior (Unequal Fracture “Wings”),
- Connection through natural fracture systems (usually temporary),
- Near-wellbore Stress Shadowing & Far-Field Fracture Shadowing,
- Fracture coalescence – Multiple Fractures Joining into One Fracture,
- Hydraulic and Stress Responses. Mechanical or Physical Damage.
- Chemical: wetting / emulsion / changes
- Time Element Factors: Immediate or Delayed Interactions

Thank You

George E. King, P.E. gking@vikingeng.net (281) 851-8095 Houston, TX

For Viking Engineering in OKC – Phil Owens, powensdsii@cox.net (405) 373-9043



Requirements – Reducing fracture driven events, casing damage and production loss.

1. Identify FDI potential for offset (passive) well(s) before the active frac.
2. Note which areas of the active well are closest to the passive well(s).
3. Note which area(s) of the passive wells are the most pressure depleted.
4. Pay particular attention when active fracturing offset to these passive well area(s). Be prepared to react rapidly if the pressure signature warrants.
5. Actively monitor the BHP in offset well(s).
6. Recognize the pressure signature(s) of fracture-to-well interactions.
7. When a fracture-to-wellbore intersection is apparent:
 - a. Make early decision(s) to reduce active well frac rate and/or reduce frac volume for the stage.
 - b. Make a quick decision on when to shut-down the job if pressure or volume reductions don't reduce/control pressure in passive well(s).

Casing Deformation & Failures via FDI

Two examples of FDI - pipe deformation/collapse and burst.

- Casing burst from fracture-driven interactions are possible when large amounts of fluid are transferred at pressures high enough to burst offset well pipe.
- Tip-to-tip frac & connections through natural fractures usually have low conductivity. Burst damage in is unlikely. This type of tortuous connection is also usually temporary and closes as fracturing pressure is bled off.
- Fracture-to-passive wellbores, (perforation clusters in same plane as approaching frac) more likely to see pressure-related damage by transfer of fluid & proppant - only this connection is likely to create burst & then only if pressure rise in passive well is high enough to exceed the current burst limits.
- Burst resistance is weakened by corrosion, erosion, damage during installation, increasing pipe ovality and loss of cement support.
- Wellhead, valves, casing and any downhole pressure barriers or equipment will be challenged.. Older passive wells equipped with low pressure rated fittings or casing are particularly vulnerable for damage from such events.
- Casing collapse in passive well may be a small to medium deformation over several joints or a severe collapse of a joint that normally stops at the coupling. This type of damage may be due to trapped pressure or pressure spikes transmitted by intersection of a fracture from the active well with a passive well in an area with no perforations. Cement quality critical.
- Bottom hole active fracture pressures can be thousands of psi. Can apply a significant collapse force to a passive well if not offset by internal pressure.

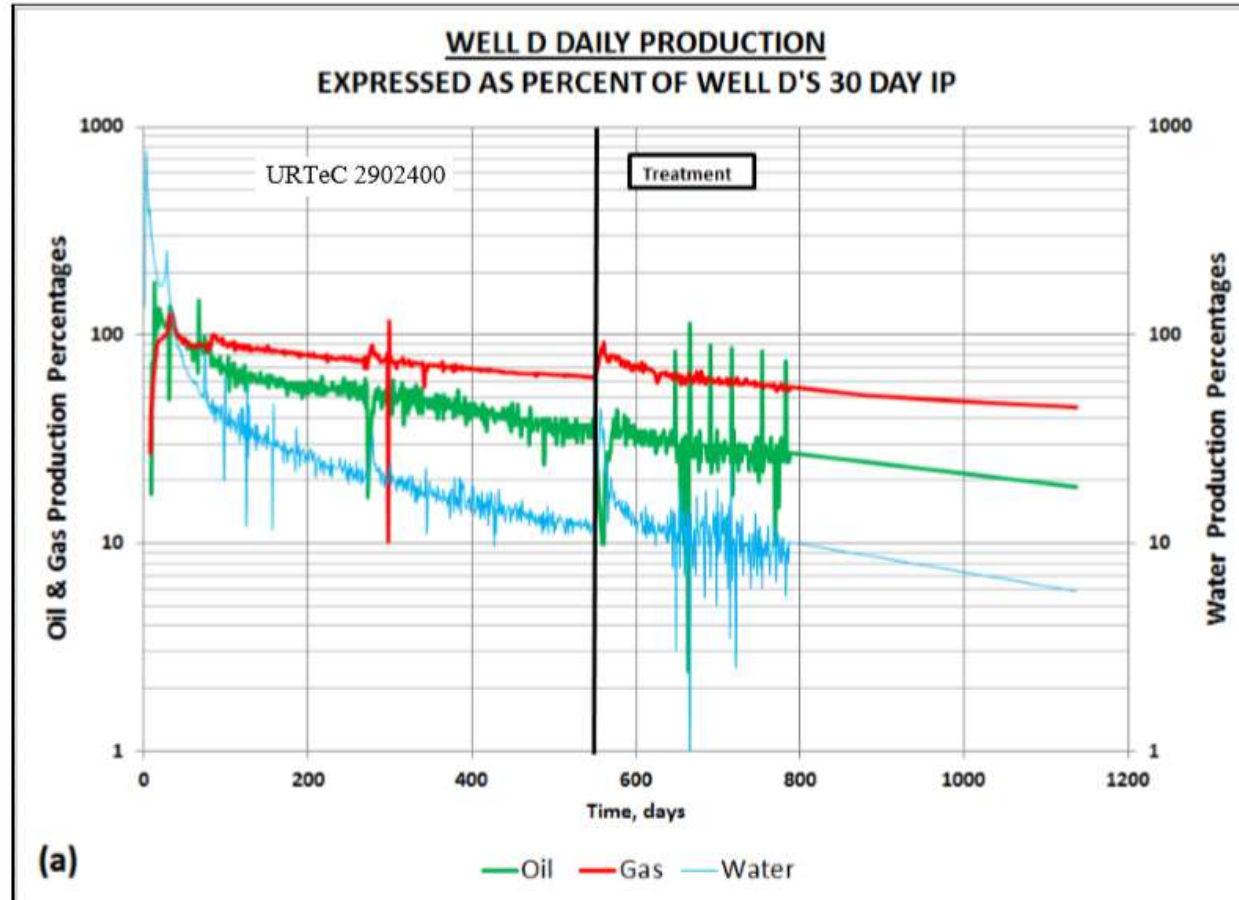
Recovery after a Frac Hit

Chemical Treatments

- **Some very successful chemical treatments after a frac**
 - **Focused on load water recovery (more popular in conventional wells?)**
 - **Focused on improving the flow passage**
 - **Finite volume of chemical only lasts a finite time.**
 - **Wetting alternation**
 - **Oil viscosity reduction**
 - **Obstruction removal or improving flow path is long-lasting**
 - **Role of acid?**

Treatment of an under-performing well

No Fracture Intersection



Some Minimization/Control Methods For FDI

- **Active**

- Monitor Passive Wells (to few psi)
- React to Monitors, Alter Frac O.T.F.
- Sequential/Simul Frac (new wells)
- Refrac Old Wells & Hold Pressure
- Gas Pressuring of Offset Wells
- Pressure Wall (Pre-Loading)
- Step-Up Frac Rate (+10 bpm incr.)

- **Passive**

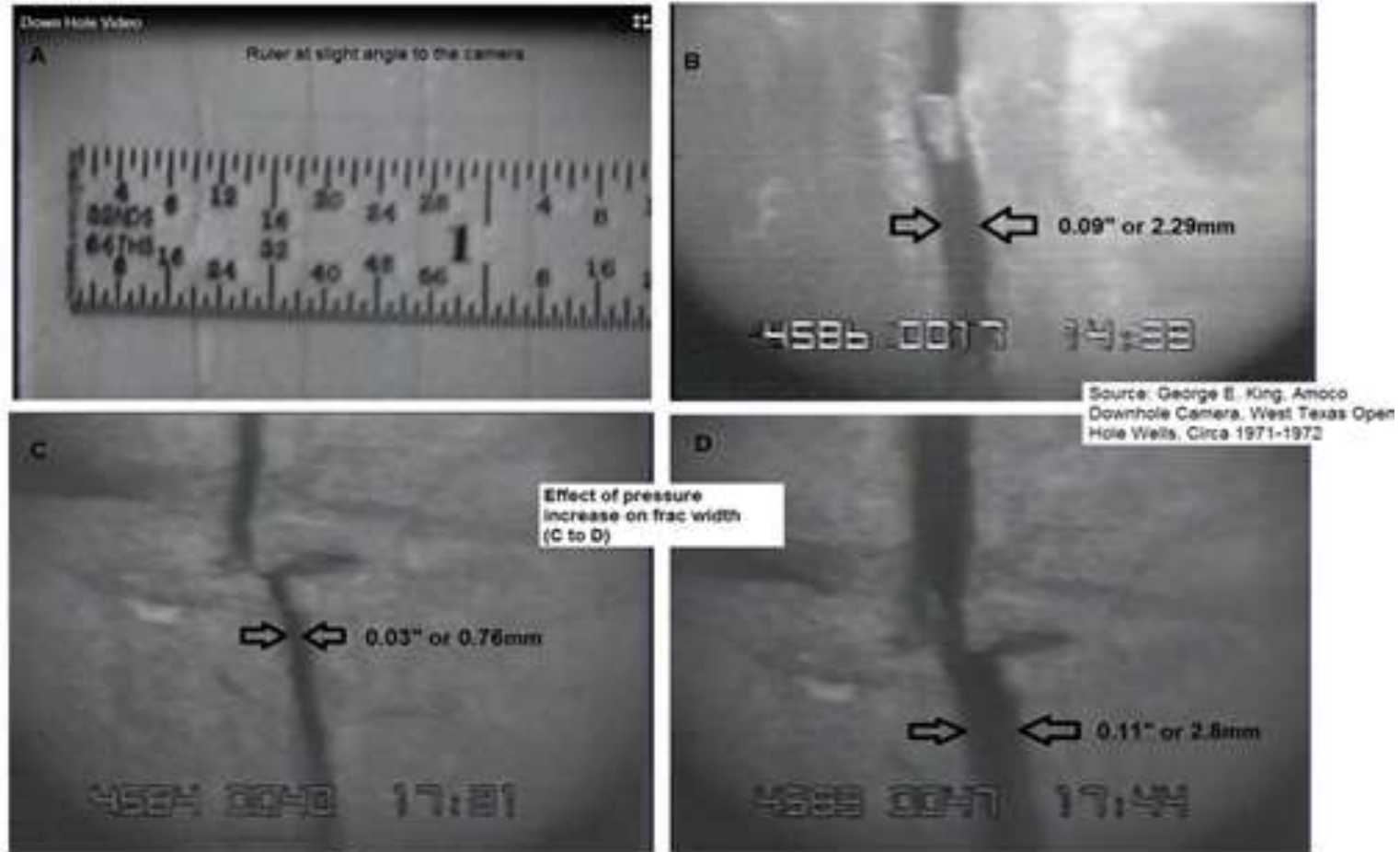
- Shut-ins (limited)
- Recognize Stress and Rock Barriers
- Well/Frac Design
 - Old perms not in new frac plane
 - Stagger vol. in depleted offsets
 - Identify local FDI drivers
 - Wider well separation (?)

No one-size-fits-all plan =>

1. Identify high risk conditions and wells.
2. Formulate passive and active control plans.

FDI Control Favors Good Designs and Active Fracturing Responses.

How Wide are Hydraulic Fractures?



Same spot, but ~4x wider frac
- upped pressure by 70 psi

Fracture Driven Interactions (FDI) between Horizontal Wells

- Nomenclature:

- Numerous types of FDI – Technical discussion content often vague.
- “Frac Hits” or “frac Bashing” only describes negative impacts.
- Active Well & Passive Well OR Parent (Monitor?) & Child (or Infill Well?),
- Active Frac – Growing frac w/ press > internal min. principle stress.
- Passive Frac – Previously Created Fracture in Passive Well.
- Frac Stage – Single Pumping Event.
- Cluster - Closely spaced group of Perforations.
- DAFI - Dynamic Active Fracture Interactions – Rx of multiple active fracs in both active and passive wells.

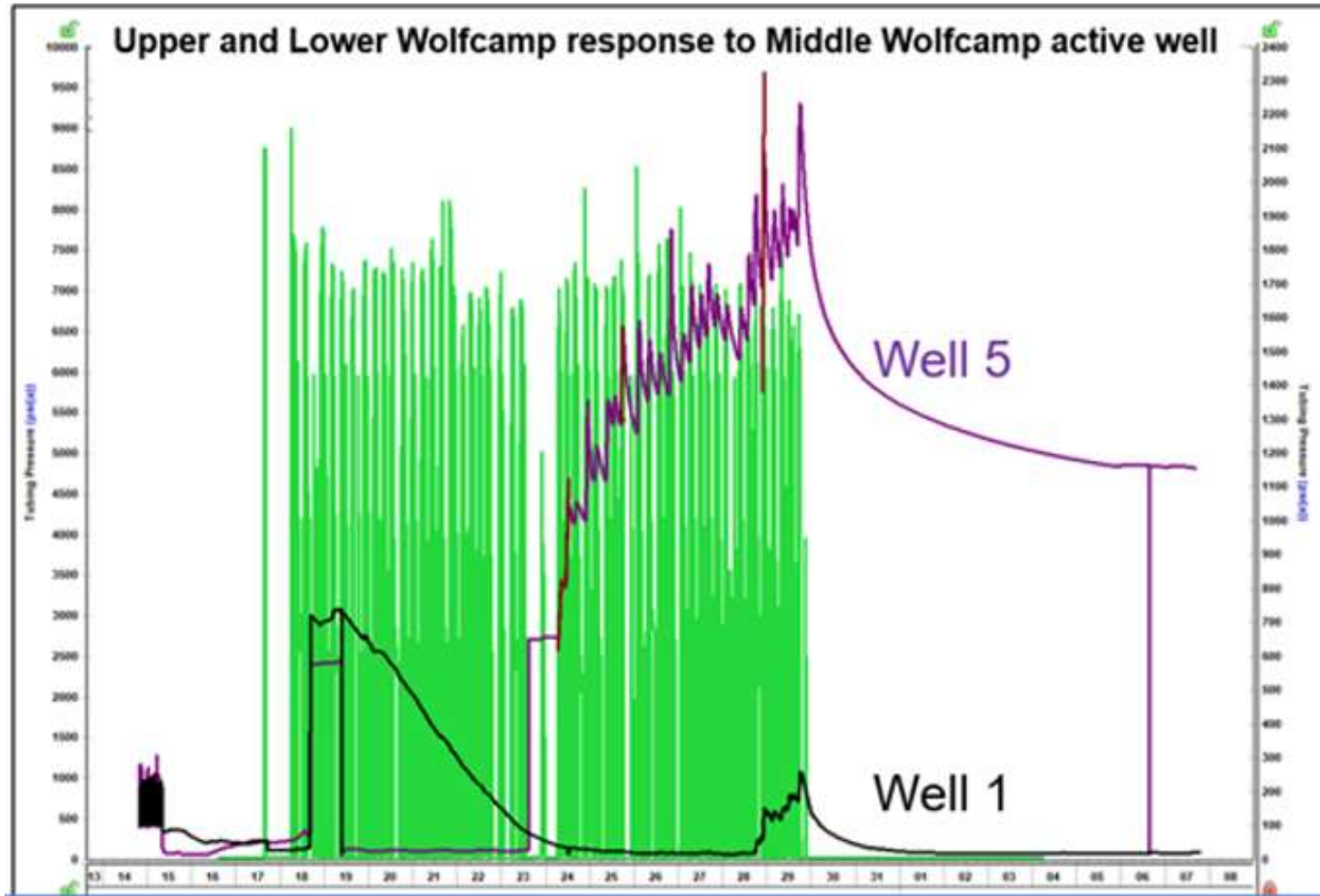
Frac intersections more common in close-spaced wells

- Rare in vertical wells in 1950's to the 80's,
- More damage to oil wells than gas ? – First clue?
- Frac hits and frac - common factors - influenced by access improvement and/or destruction along a single wellbore
 - Loss of flow path performance from proppant removal or embedment,
 - closure of unpropped fractures by changes in stress during production,
 - time between initial completion and frac-hit or frac attempt.
 - Refrac in oil zones are more successful than refracs in gas zones.
- One “thought” => Refrac appear to be more successful in basins where positive impacts from frac intersections are common. ?



Fracture Interactions, Vertical Frac-to-Frac Connections

SPE 194349-MS



Rock Fabric Variation – Complicating the Issues

Stress Changes Along the Wellbore

3D seismic interpretation by Rich and Ammerman, illustrating significant differences in seismic attributes between toe and heel of the lateral.

In their analysis, the natural fractures are parallel to fracture propagation in the toe.

In the heel, the natural fractures are oriented perpendicular to hydraulic fracture direction.

An alternate interpretation is that the differences between σ_{\min} and σ_{\max} are decreasing in the heel and are in the range that both fracture sets could grow => complexity is developed.

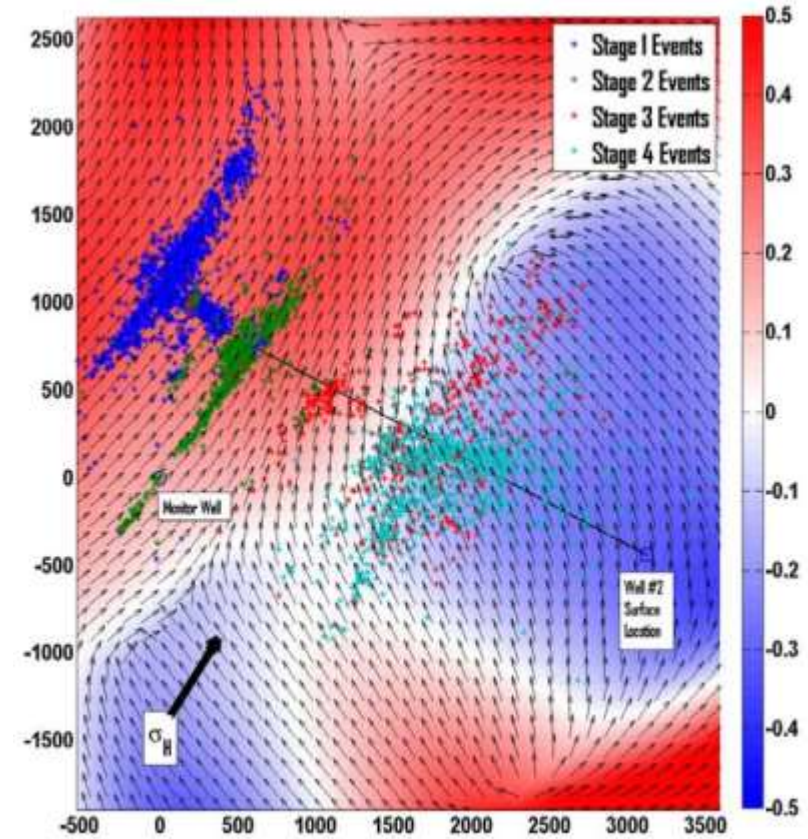


Figure 3 - Advanced seismic interpretation (from SPE 131779)